Computational Cartography - Cartography meets Computational Geometry

December 15, 1999

Contents

Introduction

Cartography has a history of several thousand years. With some right it can be claimed to be one of the earliest branches of science. All the way through its history, cartography has also had an intimate relationship with geometry. In fact, the term ıgeometryɹ (which includes the Greek root ıgeosɹ for ıEarthɹ) reveals that the origins of geometry and cartography (which to a large part was and is devoted to the depiction of the Earth on maps) are in fact the same. Map making required the mastery of geometric principles in order to tackle cartographic problems such as map projection, positioning, and measurement. Computational geometry is a relatively new branch of science. Yet, with the move from manual geometric construction to geometric computation several øelds of science and engineering have an urgent need for eŒcient and robust geometric algorithms and data structures. Cartography is among these disciplines in need of sound algorithmic solutions to its geometric problems. Some problems that were highly cumbersome and complex to solve in manual cartography such as projection transformations or the construction of 3D or panoramic maps are easy to solve today by means of geometric algorithms. On the other hand, some problems which are the ıbread and butterɹ of manual cartography, such as map generalization or the placement of symbols and labels on maps, are still largely withstanding an automated solution. And it is for these problems that interdisciplinary collaboration is necessary in order to advance the research frontier, with cartographers and specialists of geographic information systems (GIS) typically providing cartographic expertise, problem deønitions, and a ørst cut at technical solutions, and with specialists of computational geometry providing the experience of algorithm crafting, thus leading to improved algorithms.

This Dagstuhl seminar was the second one on computational issues of digital cartography, and like the ørst one, it brought together a range of specialists from cartography, GIS, computational geometry, spatial databases, and spatial analysis, with a common interest in the application of computational geometry to problems of modern cartography and GIS. Two topics, map generalization and map label placement, showed a certain concentration of talks. In these areas, it was interesting to note that a number of speakers presented methodologies that integrate geometric algorithms with optimization techniques and evaluation or cost functions. Other topics included the analysis and visualization of digital terrain models; spatial analysis for exploratory interpretation of spatial phenomena; polygon overlay problems for massive data sets; pattern recognition

for geometric and topological structuring of cartographic data; graph algorithms (graph drawing, network schematization, cross-country shortest path); and the integration of geometric data models in spatial DBMS.

As a special feature, eight representatives from R&D divisions of GIS and mapping software vendors were invited to this seminar. The objective was to expose academics and industrial representatives alike to each others' viewpoints, visions, and needs. The industrial representatives were also invited to give a demo of their system of thirty minutes and share their viewpoints and perspectives with the academic participants in an industry panel session. In the opinion of both academic and industrial seminar participants, the involvement of industry representatives worked very well.

The organisers

Martien Molenaar
Marc van Kreveld
Frank Wagner
Rob Weibel

Participants

Pankaj Kumar Agarwal
Natalia V. Andrienko
Mathieu Barrault
Antoinette Beckert
Joachim Bobrich
Martin Breunig
Marc-Olivier Briat
Dirk Burghardt
Robert Cromley
Paul Dur
Alon Efrat
Andrew Frank
Chris Gold
Annette Halbhuber
Jean-Francois Hangouet
Paul Hardy
Martin Heller
Klaus Hinrichs
Lorenz Hurni

Michael Kaufmann
Ajay Mathur
Martien Molenaar
Corinne Plazanet
Alan Saalfeld
Jrg-Rdiger Sack
Monika Sester
Jack Snoeyink
Tycho Strijk
Jan Vahrenhold
Steven van Dijk
Marc van Kreveld
Peter van Oosterom
Jan W. van Roessel
Dorothea Wagner
Frank Wagner
Robert Weibel
Alexander Wolœ
Hongguang Yang

Abstracts

I/O-EŒcient Point Location in Planar Subdivision

Pankaj K. Agarwal
Duke University
This is joint work with L. Arge, G. Brodal, and J. S. Vitter

We present an eŒcient external-memory dynamic data structure for point location in monotone planar subdivisions. Our data structure uses $O(N/B)$ disk blocks to store a monotone subdivision of size N, where B is the size of a disk block. It supports queries in $O(\log_B^2 N)$ I/Os (worst-case) and updates in $O(\log_B^2 N)$ I/Os (amortized).

We also propose a new variant of B-trees, called *level-balanced B-trees*, which allow insert, delete, merge, and split operations in $O((1 + \frac{b}{B} \log_{M/B} \frac{N}{B}) \log_b N)$ I/Os (amortized), $2 \leq b \leq B/2$, even if each node stores a pointer to its parent. Here M is the size of main memory. Besides being essential to our point-location data structure, we believe that *level-balanced B-trees* are of signiøcant independent interest. They can, for example, be used to dynamically maintain a planar st-graph using $O((1 + \frac{b}{B} \log_{M/B} \frac{N}{B}) \log_b N) = O(\log_B^2 N)$ I/Os (amortized) per update, so that reachability queries can be answered in $O(\log_B N)$ I/Os (worst case).

Exploratory Analysis of Spatially Referenced Data Using Interactive Visualization and Data Mining

Natalia T. Andrienko
GMD
http://ais.gmd.de/KD/

Geographic Information Systems (GIS) and Knowledge Discovery in Databases (KDD) have so far been developed as two separate technologies. Recently, as organizations have accumulated huge databases with a high percentage of geographically referenced data, they become interested in realizing the potential of information hidden there. The task of applying data mining technologies to spatially referenced data is therefore now becoming extremely relevant. Current results of integration of the cartographic visualization system Descartes and the data mining tool Kepler are very promising. The system Descartes developed at GMD (German national research center for information technology) provides unique features (i) for intelligent mapping support and (ii) a full spectrum of functions for interactive visual analysis of spatially referenced data. Thus, Descartes automates the generation of maps presenting user-selected data, and it supports various interactive manipulations of map displays that can help to reveal important features of the spatial distribution of data. Descartes also supports some data transformations eœective for visual analysis, and supports the dynamic calculation of derived variables by means of logical queries and arithmetic operations over existing variables. Kepler, also developed at GMD, is a data mining system that provides an easy-to-use, Æexible, and powerful platform incorporating a number of data mining methods. It is an open platform: it supplies a universal plug-in interface for adding new methods. Kepler supports the whole data mining process including tools for data input and formats transformation, access to databases, querying, management of (intermediate) results, and graphical presentations of various kinds of data mining results (trees, rules, and groups). In great extent, both systems are designed to serve the same goal - to help to get knowledge about data - but provide complementary instruments with a high potential for synergy. To further support the analysis of spatially referenced data we realized a ørst link between Kepler and Descartes, thus

integrating traditional data mining instruments with interactive cartographic visualization tools. The basic idea is that an analyst can view both source data and results of data mining processes in the form of maps and statistical graphics that convey spatial information in a natural way. The analyst can thus much easier detect spatial relationships and patterns. Conceptually the integrated system combines three kinds of links: 1. From "geography" to "mathematics": when visually exploring and manipulating a map, the user may detect some spatial phenomenon. He may then try to ønd an explanation or justiøcation for this by applying data mining methods. 2. From "mathematics" to "geography": data mining methods produce results that are then visually presented and analyzed on maps. 3. Dialogue between "mathematics" and "geography" (linked displays): graphics representing results of data mining in the usual (non-cartographic) form are viewed in parallel with maps, and dynamic highlighting visually connects corresponding elements in both types of displays. The integrated system has a client-server architecture. The server is implemented in C++ (Descartes) and Prolog (Kepler), the client in Java. The system is available for Windows and Unix platforms. Product version of Descartes and Kepler are available from Dialogis Software & Services GmbH.

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Cartographic Quality and Label Placement

Mathieu Barrault
Universitt Zrich
Geograøsches Institut

Lettering is of prime importance for maps, but positioning is a time-consuming process. Furthermore, linear features are most complex to label. This paper introduces the main parameters that guide positioning, and addresses the problems that linear label placement entails. Then, an approach for automated hydrographic name placement is presented, which takes all the quality parameters into account. It is based on the construction of a set of fundamental lines computed by a morphological closure applied on sections of the polyline split onto highly curved points. Label candidates are then tested along this øtting fundamental lines. Candidates for labeling are then selected by a mathematical

function which includes the most signiøcant qualitative parameters. Final labels of the linear feature are selected so as to guarantee a good quality for each label but also to ensure as much as possible a regular placement all along the feature. A research system has been implemented according to this approach. The results achieved so far indicate that the modeling we use allows to meet high quality requirements.

The Cartographics Production System CPS

Antoinette Beckert
Concept Software GmbH

Cartographics Production System CPS is a set of automated cartographic tools based on the ArcInfo Geographic Information System (GIS). CPS is an application developed to take care of every facet of map production, from database management to high quality output.
Emphasis has been laid on the creation of a production system with user and workÆow management. The user control allocates three categories of users, which usually exist in a production environment, all having diœerent access to the system.
In CPS we have chosen to build and maintain separate, yet linked, databases. The geometrically correct base data is stored with the highest possible accuracy in a master database (MDB). Generalized or derived data is stored in scale dependent product databases (PDBs). CPS supports all ArcInfo input formats. The main problem with multiple representations of the same object is to maintain data consistency. In the MDB-PDB model, functionality to check consistency between the product databases and the main database has been implemented through the feature-based links, and through the use of the history functionality of the databases. It is possible to query the master database for features which have been changed (added, deleted and modiøed) since the last update of the product databases. The edited features can be extracted and automatically transferred to the product databases.
The ability to automatically check that a speciøc product database is up-to-data is extremely valuable in a production environment. Resources can be focused on the maintenance and management of one database (the master database), and the product databases can be updated as needed.
CPS is implemented as an open system. This allows full customization of CPS while maintaining access to all of the tools of ArcInfo. In addition, users themselves can develop their own applications to support unique requirements.
CPS has a new more cost eŒcient structure. The four CPS components can be combined for a production environment customized for the user organization.

Cartographic Displacement Using a Physical Model

Joachim Bobrich
Universitt Hannover
Institut fr Kartographie

Displacement as a consequence of lettering or enlargement of map objects, above all on small-scale maps, is the most complex phase within generalization of maps.

Zones of high or too high information density must be relieved or eliminated by appropriate measures in order to guarantee the content of information of a map. Special requirements of the users have to be taken into account, i.e. spatial reference of same objects has to be of higher importance than that of other objects.

Beginning from a general description this approach transfers of the characteristics of map objects into a pseudo-physical model with attributes dynamic characteristics to each object of the map and so allows a diœerential displacement of the diœerent signatures. The hybrid displacement approach describes at the vector side the persistence behaviour of the map objects at their original place by simulated suspension an elastic springs and their induced, internal potential..

The spatial displacement eœect or external potential is described by means of raster data and their areal properties and processing possibilities.

The optimal solution is found by minimization the displacement potential $Pos_{displacement} = Pos_{internal} + Pos_{external}$ by an heuristic optimization-algorithm called ıdownhill-simplexj.

Building Geo-Scientiøc Applications on Top of GeoToolKit

Martin Breunig
Universitt Bonn
Institut fr Informatik IV

Today's geo-information systems are historically grown products which are hardly extensible to meet the requirements imposed by 3D/4D-modeling. The next generation GISs should beneøt from modern software engineering technologies. A component-based design encourages a fast "assembly" of applications from high-level software building blocks. Following this approach a complex general-purpose geo-information system can be substituted by a family of specialized subsystems which due to the common design basis are open for mutual data exchange. In this talk GeoToolKit - a component software intended for the development of 3D/4D geo-scientiøc applications is presented. Also experiences in building diœerent types of applications on top of GeoToolKit are given and open problems are discussed.

DataDraw : a modeling platform for cartographic problems on top of a database.

Marc-Olivier Briat
Hemispheres - Paris

Databases are more and more linked to cartographics systems. The point is that geographic informations ønd their place into databases, even the relational ones. Customers are very interested in this approach, because it uses tools they already know. DataDraw is designed to make this databases graphical. It provides a set of tools to build the cartographic drawing only with informations coming from the database. DataDraw provides a way to store these informations (color, line width, etc.) directly in the database. All these graphical attributes allow a great variety of symbolizations, that can be diœerent for each object within one class,

but using the same table/column structure. One of the major functionalities is the capability of using multi-geometric øelds in the database, each one allowing to position a new graphic element, but preserving the integrity of the data structure. It is no longer needed to have two objects describing a feature and its name for example, but instead you will have two styles applied on the same table containing the positions of the two graphical features. It appears that this way to model information is useful to describe a cartographic database (designed to print paper maps), but also to manage informations related to geomarketing problems, where people is not necesseraly aware of GIS particularities. One of our future works is to consider the symbolization elements as a database, improving therefore the tools to handle this kind of informations.

Coastline Feature Generalization Using Constrained Delaunay Triangulation

Robert Cromley
University of Conneticut
Dept. of Geography

Two approaches have been taken with respect to the generalization of naturally occurring lines - the elimination of points along a line and the elimination of features in a line. Most early work in line generalization focussed on the former as exempliøed by the Douglas-Peucker routine. This approach to generalization sometimes results in self-crossing lines and an over simpliøcation of features because of its inability to remove any features. The method presented here for generalizing coastlines ørst identiøes features in the coastline and successively removes the less important features. A constrained Delaunay triangulation of polygon results in a decomposition of the polygon into triangles that share either two sides of their edges with the polygon outline, one side of their edges with the polygon or no sides of their edges with a polygon. A constrained triangulation of a coastline with its associated islands and inlets are ørst divided into those triangles comprising the sea versus those that make-up the land. In the initial algorithm, sea triangles are classiøed into those triangles having two land-sides, one land-side, or no land-sides. A triangle with two land-sides identiøes the terminus of an inlet; the full inlet will continue through a series of one land-sided triangles until a no land-sided triangle is encountered. A water pass between land will consist of a series of one land-sided triangles terminated on both ends by triangles having no land-sides. The procedure consists of converting sea inlets to land area by removing minor inlets and sea passes based on their area. As an inlet or a pass is eliminated, the remaining triangles are recoded based on the number of land-sides and the process is repeated. Self-crossing lines are not possible in this method because areas are removed rather than points along a line. The method is illustrated by successively generalizing a section of the southwestern coastline of Norway.

From digital data to a high-quality cartographic document

Paul Dur
Barco Graphics

When cartographic publishers turned to GIS-based solutions to produce maps, atlases and other cartographic documents, they expected to obtain the following: higher productivity through automation, Æexibility in deriving new products and more secure storage of the basic production data. The guiding principle in this transition was the preservation and possibly the enhancement of the cartographic quality - in particular the informativeness and legibility of maps and charts. This is where GIS has failed because in order to obtain this quality, GIS output (usually PostScript-based) has to be taken through a lengthy process of interactive (i.e. manual) post-editing, losing almost completely the automation and with it the Æexibility of digital methods.

In this presentation, we discuss the basic design principles through which `MERCATOR`, the cartographic publishing system developed by Barco, allows cartographers to generate documents in a fully automatic way and still reach and even surpass the quality of manual methods. The system is built on a clear separation of data content and representation. It provides a common data format that allows both to combine data from multiple sources and to derive many diœerent products from these combined sources. The layer-based map model enables the use of selective masking techniques that guarantee the legibility of text. The informative quality of the maps is enhanced through full support of transparency and the use of an additive color algorithm, all in WYSIWYG mode. As a map usually does not constitute the complete cartographic document, `MERCATOR` allows the automatic addition of components such as covers and legends from diœerent (possibly 3rd party) sources. The end result of the `MERCATOR` procedures is a digital document that is completely ready for output.

EŒcient Regular Data Structures and Algorithms for Location and Proximity Problems

Alon Efrat
Stanford University
The talk is based on the paper ıEŒcient Regular Data Structures and
Algorithms for Location and Proximity Problemsj, by A. Amir, A. Efrat,
P. Indyk and H. Samet, which will be presented in FOCS 1999.

In this talk we describe algorithms and combinatorial bounds for variant of Quadtrees. Assume the input for all problems is taken from an integer grid of size $u \times u$. We showed in the talk the following three results:

- Given a region Quadtree contains n nodes, we can compute the dilation $D_r(T)$ of the shape that T represents with a disk of radius r, in time $O(n)$. Moreover. $D_r(S)$ can be stored in a compressed segment quadtree that contains $O(n \log u)$ nodes.

- Given an (either region or segment) quadtree of n nodes, we can store these nodes in a (dynamic) data structure of size $O(n)$, so that one can determine if a query integer point q lies within the region represented by T in expected time $O(\log \log u)$. Moreover, the same result holds also for compressed quadtree, but the size of the data structure in increased to $O(n \log \log u)$.

- We show that if S is a shape in the plane consisting of the (not-necessary disjoin) union of n *fat* object, then S can be stored in a segment quadtree of size roughly $O(n \log u \log \log n)$.

Models of Map Production and Use

Andrew Frank
Technische Universitt Wien
Inst.fr Geoinformatik

Maps are used in many situations to guide our decisions in space. Maps are an eœective way to collect, store and communicate spatial information. In this presentation I use an approach based on multi-agent systems to explain the communication using maps.
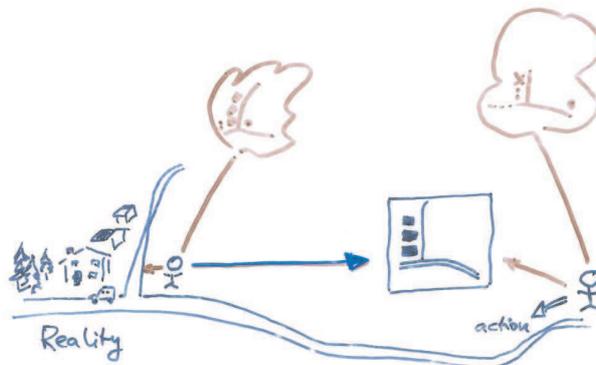
An agent observes the world and forms a mental map of the reality she observes. The mental map of the observer is then expressed in a physical form - for example, as a cartographic product. Another agent acquires this cartographic product and interprets it; she forms a mental map based on the cartographic product studied. The second agent then makes a spatial decision using the map. The cartographic product (the map) is eœective if the decision the second agent makes based on its use is the same she would make based on a direct, personal investigation of the world. For example, if the second agent wants to walk to the third building on the small road, and decides on going along the main road and then turn right and stop at the third building, then the execution of this plan will actually and correctly lead him to the desired location. Therefore the map is eœective for this use.

The multi-agent approach gives a framework for the discussion and systematic investigation of a number of long-standing problems in cartography:

- The ørst agent observes the world with certain data collection processes, which retain and encode some properties of reality and leave some other out. This models the rules of cartographic data collection.

- The mental model the ørst agent constructs may be in error.

- The encoding of the mental model in a physical map follows the rules of cartographic representations (and the process may also be inÆuenced by

errors).

- The second agent uses a set of rules to ıreadJ the map and construct his mental map. Here systematic errors of interpretation are possible.

- When using the mental map to make a decision about actions she may make errors.

Maps are eŒcient if random errors are not signiøcant or are correctable due to redundancy, and if the data collection process and the processes which use the data are conceptually related, i.e., relate to the same physical properties.

A One-Step Crust and Skeleton Algorithm

Chris Gold
Universit Laval
Centre de Recherche en Gomatique

Amenta, Bern and Eppstein (1998) gave a method for extracting the crust (or boundary) from an unordered set of input points, being samples of a curve. We show that both the crust and the skeleton may be extracted from the simple Voronoi diagram/Delaunay triangulation by a simple test which assigns each Voronoi/Delaunay edge pair to either the crust or the skeleton.

As the sample points often possess positional error in practice, the resulting skeleton may have ıhairJ, branches generated when three adjacent crust vertices form a Voronoi vertex. Generalization, in the form of skeleton simpliøcation and boundary smoothing, may be achieved by retracting the skeleton leaf nodes to their parent locations. This is particularly useful when using the skeleton to represent the shape or topology of map objects.

Interesting examples include descriptors of polygon shape, estimation of watersheds from hydrological networks, text recognition, extraction of topology from scanned maps, and generation of triangulation models from contour input.

Automated Spatial Analysis and the Naturalness of Voronoi Diagrams

Jean-Francois Hangout
IGN/Cogit

Some basic or recurring spatial queries on vector data are shown to be made easy and exact by the precomputation of the segment Voronoi diagram. Why such eŒciency? It is argued that the Voronoi diagram on segments is a perceptually, mathematically, procedurally and geographically natural structure for GIS data, inasmuch as it belongs with the data themselves, independently from applications (while Delaunay or Voronoi on points are application- induced structures).

Computing the data from a Voronoi is a $O(n)$ problem: data are contained within their Voronoi. Computing the Voronoi from data is a $O(n \log n)$ problem. Information is gained, which can be formulated as follows: the Voronoi diagram projects the separated digital data into their expected map-like state, which makes automation of map-reading more intuitive.

Active Object Techniques for Map Generalisation and Dynamic Generalisation

Paul Hardy
Laser-Scan Ltd.

Cartography has traditionally been an isolated task, compiling information from various sources to produce a particular cartographic product. This traditional view is now being replaced by one centred on building a master database modelling the real world. From this database are then produced multiple maps, charts, geospatial data, and on-demand spatial visualisations such as Internet web mapping.

This paper and demonstration overviews a modern production application (Laser-Scan's Gothic LAMPS2) built on an object-oriented geospatial database, and speciøcally highlights its capabilities for integrity enforcement, dynamic representation, multiple geometry, and automated generalisation, in order to explore the beneøts and future directions of active object mapping.

Active generalisation methods rely on message passing to objects to ask them to simplify or displace themselves. Dynamic representation implemented as active object display behaviours allows individual objects to draw themselves diœerently according to their surroundings, or as needed for a speciøc product. Distributing the knowledge of selection, generalisation and representation into object behaviours in this way overcomes many of the problems previously encountered in embedding the skill of the human cartographer into a software solution

The presentation is interleaved by live demonstrations of the LAMPS2 software, covering the object data model, database versioning, dynamic topology creation, active representation, multi-product alternatives, and object-oriented generalisation.

Terrain modelling with tension minimizing triangular meshes

Martin Heller
Universitt Zrich
Geograøsches Institut

Our research focuses on adaptive interpolation methods for structured terrain data. Our goal was to ønd a technique that imitates the approach of an experienced morphologist. The resulting procedure should be able to accommodate stylistic guidance from an operator, but should generate reasonable surfaces even without additional structural information. We designed a program that simulates a relaxation process of a Æexible surface. Our approach diœers from similar existing ønite element methods by not using a completely smooth rectangular grid, but a non-homogeneously elastic and partially creased triangular mesh instead. The procedure starts by ønding relevant discontinuities and estimating local elasticity. An optimization process then produces a surface that approximates the observation points while minimizing tension. For this purpose, we had to ønd a way to deøne local elasticity/rigidity of the surface, a scheme to generate a øne triangular mesh, a procedure to solve the resulting sparse

equation system and a method to ølter the mesh to produce a triangulation with required resolution.

Future research will concentrate on ways to adequately integrate structural know-how.

Algorithms for Performing Polygonal Map Overlay and Spatial Join on Massive Data Sets

Klaus Hinrichs
Westflische Wilhelms-Universitt Mnster
FB 10 Informatik
This is joint work with L. Becker, A. Giesen, and J. Vahrenhold

We consider the problem of performing polygonal map overlay and the reønement step of spatial overlay joins. We show how to adapt algorithms from computational geometry to solve these problems for massive data sets. A performance study with artiøcial and real-world data sets helps to identify the algorithm that should be used for given input data.

Cartographic Design in a Digital Production Environment

Lorenz Hurni
ETH Zrich
Institut fr Kartographie

What is the aim of the map? Who are the users of the map? Usually, these are the two main questions to be answered before starting a new map(ping) project. Using this information, base data and thematic data must be collected, an adequate map model as well as the ısign languageȷ (map symbolisation) and the publication medium must be chosen. Unfortunately all these steps inÆuence each other and they can even interfere. Usually, a very time-consuming modelling and design process is necessary in order to harmonise them. In a digital cartographic production system, cartographic data is often imported from existing GIS sources and therefore must be adapted and converted to meet the necessities imposed by the cartographic model and the symbolisation. The design process, which can also comprise generalisation steps, can be characterised as the total of a set of local or global single actions. Very important is also the orchestration of these actions in order to create an optimal co-ordination of the map elements (ıZusammenspiel der Elementeȷ). This process is diŒcult to deøne because a) even cartographers often fail to describe the cause of a speciøc action and b) the geometrical conøguration and the content change on every map.

At the Institute of Cartography at ETH Zurich, a major focus of application-oriented research activities is devoted to the development of interactive tools in order to automatise or support speciøc steps in the cartographic design process. The following tools have been presented at the Dagstuhl-Seminar:

- Import of GIS-Data: Line thinning, Bzier interpolation

- Line thinning and edge building (e.g. with vectorised data)

- Area building

- Bzier interpolation for cartographic design

- Placement and design of hedges

- Rectiøcation of buildings

- Minimisation of area colours

- Digital cliœ drawing

Maptech Presentation

Ajay Mathur
Maptech AG

1. Introduction

   With the growing availability of high quality digital data, the need for automated generalization solution for the production of maps and map related data is becoming urgent. Applications for the derivation of topographic maps out of geo-topographic data base ATKIS in Germany are currently being developed. A diœerentiation is made between model and cartographic generalization. Model generalization includes simpliøcation of data while changing map scale without considering the cartographic presentation, for instance, derivation of data model 1:50'000 from base model (1:5'000 or 1:10'000 ATKIS/DLM). Cartographic generalization, characterized by functions like simpliøcation, enlargement, displacement, aggregation, selection, classiøcation etc., are necessary for creating cartographic presentation out of geo-topographic data bases.

2. Maptech Products

   - maptech Capturing: Conversion of analog maps and plans to high quality geo-data by means of automated vectorization and object recognition.

   - maptech Geo-data management: Object relational seamless geo-database High-performance data access Oœers true integration (object structured) of data from various GIS

   - maptech Mapping: Covers the entire production line of digital cartography. Oœers WYSIWYG environment while working with spatial data which includes:

     ˘ preparation work on map symbolic
     ˘ update, editing geo-data
     ˘ map production, map edition, map design
     ˘ sophisticated colour separation

3. Automation and generalization functions. Automated cartographic displacement

The automation of elementary generalization functions is the ørst step to a completely automated derivation of digital topographic maps from digital data. Displacement functions are diŒcult to automate. The method of energy minimization is used for solving problem caused by overlapping and too short distances (external energy) between objects. Line and area objects can be displaced while maintaining their typical shape.

The modelling of line shape is achieved with the help of active splines, so called "snakes". As opposed to application in the øeld of image-processing, the changes in the splines' expansion and curvature characteristics are referred as internal energy.

A demonstration of line and area displacement (lines, buildings and text conÆicts) was presented using the Maptech Mapping System.

4. Maptech Priorities

- short term:
  - ˘ automated map edge work (AURA) allowing automated displacement and suppression of text and symbols at the map boundaries.
  - ˘ adjustment of data from diœerent source (e.g. to integrate houses from ALK cadastre in the geo-topographic data ATKIS)
  - ˘ automated text placement
  - ˘ automated symbol placement (related to ASTIS)
- mid term:
  - ˘ automated generalization in map scale transition from 1:25.000 to 1:50.000 (derivation of DTK 1:50.000 for the Land Survey authorities in Germany)
- long term:
  - ˘ automated derivation of any map scale from one data set

The monitoring of objects with uncertain spatial extent

Martien Molenaar
International Institute for Aerospace Survey and Earth Science
(ITC)

The shape and size of area objects is traditionally determined by their boundaries. This approach is applicable for crisp objects, which do have well deøned boundaries. The spatial extent of such an object is determined by the set of faces that constitute its geometry. For these faces the relation to an object O can be expressed by a function $Part_{aa}[f, O]$ that has the value 1 when the face f is PART OF the spatial extent of O and has the value 0 otherwise. The faces can have irregular shapes as in vector maps, or rectangular shapes as in raster maps. The boundary of an object consists then of edges which have only at one side a face that is part of the O. If an object has a fuzzy spatial extent then

this consists of faces for which the function $Part_{aa}[f, O]$ has a value between 0 and 1. That means that there are no edges that have the object exactly at one side, so that no boundary can be determined. These objects will have transition zones where the function $Part_{aa}[f, O]$ fades from some positive value close to 1 down to 0. For these objects only conditional boundaries can be determined, these are the boundaries of the spatial extents deøned for some certainty levels C, i.e. the conditional extent consisting of the faces for which $Part_{aa}[f, O] > C$. A fuzzy object has a convex fuzzy spatial extent If the conditional extents for diœerent values of C are nested and connected. Natural objects should in generally be represented as objects with a fuzzy spatial extent because they rarely have crisp boundaries. An example can be found in coastal zone areas in the Netherlands where no crisp boundaries can be identiøed between foreshore and beach area, or between beach and foredune area. In these examples the objects do have convex fuzzy spatial extents. If such objects are to be monitored to determine their dynamics, then spatial behavior can not be observed through changes of the boundaries. The changes can only be determined by overlaying the fuzzy spatial extents of diœerent years and the evaluation of their similarities and diœerences. That means that no crisp answer can be found for the change in object geometry from year to year, the diœerences can only be evaluated for speciøed certainty levels.

For further reading see:
Martien Molenaar: *An Introduction to the Theory of Spatial Object Modelling for GIS*. Taylor & Francis, London, 1998, 246pp. ISBN 0-7484-0775-8 (cased) ISBN 0-7484-0774-X (paper)
Tao Cheng: *A Process-Oriented Data Model for Fuzzy Spatial Objects*. ITC publication Series, No 68, ITC, Enschede, 1999, 163pp. ISBN 90-5808-038-2

SeaÆoor Relief Modelling

EPFL
Lab. de Bases de Donnes

A theoretical approach to the description of local seaÆoor relief shapes has been presented in extension to [1] for further possible discussions during the seminar. A scale independent model have been proposed which consists of a 3D schematized representation (skeleton) of the local seaÆoor features, i.e. most notably elongated features such as valleys and ridges. Shape skeletons are generated by computing sections orthogonally along ridge and valley lines extracted from the original bathymetric proøles. The local shape descriptive model is composed of symbolic and geometric description of characteristic shape features and related vertical sections. Such a model enables either relief shape interpretation, and further complementary elements to the global DTM manipulation. Furthermore, it aims at enriching our current knowledge on seaÆoor shapes by providing tools for local schematized visualisation of the seaÆoor features, or further qualitative and quantitatve elements for shape interpretation and relief recognition.

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Corinne Plazanet, Michela Spagnuolo. SeaÆoor Valley Shape Modeling. In *Proceedings 8th International Symposium on Spatial Data Handling*. Vancouver (Canada), July 1998, pp 751-761 `http://lbdwww.epfl.ch/~corinne/pubs.html#Seafloor`

Area-Preserving Piecewise-AŒne Mappings

Alan Saalfeld
Ohio State University

If P_o and Q_o are any two simple polygons, and if $\Phi : \partial P_o \to \partial Q_o$ is any piecewise-aŒne homeomorphism (PAH) of the boundary ∂P_o of P_o onto the boundary ∂Q_o of Q_o, then there exists a PAH extension $\hat{\Phi}$ of Φ to all of the interior of P_o that preserves relative area size everywhere. In other words, for any subset S of P_o that has nonzero area, the subset $\hat{\Phi}(S)$ of Q_o also has nonzero area, and

$$\frac{\text{Area}(S)}{\text{Area}(\hat{\Phi}(S))} = \frac{\text{Area}(P_o)}{\text{Area}(Q_o)} = \text{a constant}$$

In particular, if $\text{Area}(P_o) = \text{Area}(Q_o)$, then the constant is 1, and $\hat{\Phi}$ is area preserving everywhere: $\text{Area}(S) = \text{Area}(\hat{\Phi}(S))$ for all S.

Proof sketch: Isomorphic triangulations induce piecewise-aŒne homeomorphisms. For two equal-area quadrilaterals, we may ønd either one or two Steiner points in each of the quadrilaterals to produce isomorphic triangulations for which each triangle in the triangulation of one quadrilateral has the same area as its corresponding triangle in the triangulation of the other quadrilateral. We use induction to prove the result for any two equal-area convex n-gons, then apply induction again to extend the result to any two equal-area arbitrary n-gons.

Realistic Shortest Paths

Jrg-Rdiger Sack
Carleton University
School of Computer Science
Joint work with Lyudmil Aleksandrov, Mark Lanthier and Anil Maheshwari

Shortest path problems are among the fundamental problems studied in computational geometry. Such problems arise in numerous applications in areas such as robotics, traŒc control, search and rescue, water Æow analysis, road design, navigation, routing, geographical information systems. Most of these applications demand simple and eŒcient algorithms to compute approximate shortest paths as opposed to a complex algorithm that computes an exact path.

Motivated by the practical importance of these problems and very high complexities for computing exact shortest paths (in particular in weighted scenarios or in 3D) we investigate algorithms for computing approximated shortest paths. In this talk we describe several simple and practical algorithms (schemes) to compute an approximated weighted (and unweighted) shortest path between two points on the surface of a (possibly, non-convex) polyhedron (or a TIN).

We also describe ϵ-approximation algorithms for such problems. While these algorithms have a more complex analysis their implementation remains simple. Furthermore, we sketch our work on shortest anisotropic paths on terrains. Anisotropic path costs take into account the length of the path traveled, possibly weighted, and the direction of travel along the faces of the terrain. Considering faces to be weighted has added realism to the study of (pure) Euclidean shortest paths. Parameters such as the varied nature of the terrain, friction, or slope

of each face, can be captured via face weights. Anisotropic paths add further realism by taking into consideration the direction of travel on each face thereby e.g., eliminating paths that are too steep for vehicles to travel and preventing the vehicles from turning over.

Finally, we discuss some very recent developments in computing shortest paths in 2-D and 3-D.

Generalization based on Least Squares Adjustment

Monika Sester
Universitt Stuttgart
Institut fr Photogrammetry

Recently, an emersion of using ıforce modelsʃ to solve generalization problems, especially displacement, can be observed: the ørst were probably Burghardt & Meier [1997], who use a snake approach to displace linear elements in maps (e.g. road and rail network). Then Hojholt [1998] came up with the idea of applying Finite Element Theory as a framework for displacement. Bobrich [1999] also uses a mechanical analogon as a model, namely springs. Ware & Jones [1998] use simulate annealing as an optimization technique. Independently, Harrie [1999], Sarjakoski & Kilpelainen [1999] and Sester [1999] developed ideas to solve displacement with Least Squares Adjustment theory.

Least Squares Adjustment theory (LSA) is a well known general framework to determine unknown parameters based on given observations; the observations are formulated in terms of functions of the unknown parameters. Thus unknown parameters can be determined given exterior constraints or models. In the presentation, LSA was applied to solve two generalization operations, namely the simpliøcation of building groundplans, and displacement.

In order to generalize building groundplans, ørst a simpliøed model of the building is derived using three rules in order to remove small building structures. This results in a simple, but not necessarily correct model of the original situation. Thus, in an adjustment process, the the building model is adjusted to original building shape. In the second example, LSA is applied for the displacement: diœerent objects have to be displayed on a map - for reasons of legibility certain constraints have to be satisøed, e.g. minimal object sizes and minimal object distances have to be enforced. LSA oœers a straightforward framework to introduce diœerent kinds of constraints: object size, object form, object distances. In one step, all these constraints are solved simultaneously, resulting in one optimized solution with the feature that all residuals are distributed evenly among all the observations. Besides this result, quality parameters indicate, how well the initial constraints could be satisøed. The presentation also sketched, how LSA theory could be applied for other generalization operations, e.g. typiøcation. This, however is subject to further research.

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Visualizing Geographic Migrations and Flows?

Jack Snoeyink
University of North Carolina at Chapel Hill
Dept. of Computer Science

Geographic information systems combine heterogeneous data by assigning it a spatial position. For many processes, however, data naturally has two or more positions. I present two examples, in the hopes that the cartographers will teach me the best way to visualize such processes: point-to-point migration data, and traŒc Æow data.

To show an overall picture of migration data, we propose to use geometric spanners⁻graphs that approximate the complete graph such that any pair of nodes has a path joining them that is not more than some constant factor times the distance between the nodes. To show Æow data, we propose use non-uniform transformations, and to accelerate their computation with methods from n-body computation.

Evaluation of Quality of Map Labeling

Tycho Strijk
Utrecht University
Dept. of Computer Science
Joint work with Steven van Dijk, Mark van Kreveld and Alexander Wolœ.

The cartographic labeling problem is the problem of placing text on a map. It is composed of two phases. In the ørst, the question which map features should in principle receive a label is settled and the style (i.e." color and font) of these labels is determined. The second phase consists of the actual label placement. In this phase for each feature one has to decide whether there is in fact suŒcient space and, if yes, the best location and shape of the label must be determined. This talk proposed a quality measure for the result of the second phase, allowing the comparison of label placement programs.

Reducing I/O Operations in Spatial Join Algorithms

Jan Vahrenhold
Westflische Wilhelms-Universitt Mnster
FB 10 Informatik

This is joint work with L. Arge, O. Procopiuc, T. Suel, S. Ramaswamy, and J. Vitter.

We study the eœects of random and sequential I/O operations in spatial join algorithms. Furthermore, we develop a simple plane-sweep approach to the spatial join problem that uniøes the index-based and non-index based approaches and can be built from a few standard operations.
We also report on the results of a comparative study of the new algorithm with several index-based and non-index based spatial join algorithms. The experiments have been performed on several diœerent architectures, and scaled up to data sets that are signiøcantly larger than those used in previous work. We considered a number of factors, including the relative performance of CPU and disk, the quality of the spatial indices used, and the sizes of the input relations.

Using Genetic Algorithms to Solve Hard GIS-Problems

Steven van Dijk
Utrecht University
Dept. of Computer Science

Genetic Algorithms (GA's) are powerful combinatorial optimizers based on the theory of Darwinian evolution. They work by encoding a solution to the problem in some manner and evolving a population of solutions until a close to optimal solution is found. An objective function is needed to assign a øtness to a solution. The talk aims to introduce and describe the main principles of GA's. It will show that in order to build an eŒcient GA one needs to exploit the structure (or *linkage*) of the problem. In GIS-problems the linkage is easy to determine because it is induced by the geometry of the problem. This makes GA's especially well suited for solving them.
An implementation of the GA to solve the problem of map labeling was described and it was shown that the GA performed very well.

Schematization of road networks

Marc van Kreveld
Utrecht University
Dept. of Computer Science
Joint work with people from the applied algorithms group at Utrecht
University

Road networks consist of junctions with speciøc locations in the plane, and connections or roads that have a speciøed shape and connect a pair of junctions. In other words, a road network is an embedded planar graph where the arcs have a speciøed shape.
The problem of road network schematization consists of making a schematic, diagram-like representation where the shape of the arcs is simpliøed to only two or three segments. Usually these segments have to be axis-parallel or 8-oriented. We analyze a couple or requirements that can be used in road network schematization, identify the types of connections that can be of interest, and present

two approaches to solve such problems. Requirements typically are no crossings of schematized roads, a minimum distance between two roads, keeping the embedding of the network the same, and making through-going roads at junctions to be extensions of each other. Types of connections include 4-oriented or 8-oriented connections, shortest connections in the L_2 or L_1-metric, and so on. The ørst approach to solve schematization is based on reduction to a 2-SAT formula whose solution gives the shape of the schematized connections. The second approach tries to establish a top-to-bottom placement order such that the schematized roads can be placed topmost in this order, without restricting any possibilities of roads to be placed later. Finally, we gave an algorithm to compute a closest Hausdorœ distance schematization of a road.

Rule-based Polygon Classiøcation of Topologically Structured Topographic Data converted from Spaghetti Data

Peter van Oosterom
Dutch Cadastre
`http://ooa.kadaster.nl/~oosterom/fin.html`

In this paper the migration of a spaghetti to a topologically structured topographic base map is discussed. Investigations into this subject are going on for a couple of years now. Speciøcally the rule-based classiøcation of the areas has been implemented, tested and compared to human classiøcation.

The large scale topographic base map of the Netherlands at scale 1:1.000 in urban areas and at scale 1:2.000 in rural areas covers almost the complete country. It consists of line elements (polylines and circular arcs), point symbols an text labels. The current large scale topographic base map does not represent area features explicitly. However, human map readers are, most of the time, able to interpret the map and determine where the area features are located by looking at the lines (representing topographic boundaries), text labels and symbols. For the computer it is much harder to discover the area features explicitly.

Having area features explicitly in the map makes it possible to produce better cartographic output; for example fully colored maps. The topologically structured topographic map is better suited as basis for thematic maps by combining the basic areas to appropriate units. It is a better model of the world (Digital Landscape Model, DLM), because there is more explicit knowledge stored concerning the real world features. Having area features explicitly available makes it also easier to reason about them; e.g. apply generalization (removing objects, combining objects, simplifying objects, etc.) or at least update propagation from the large scale to the medium and small scale models. Another example is the computation of the center line of roads or waterways.

The goal of the described research is to convert the current spaghetti data set into a topologically structured data set with explicit area features at lowest possible costs. As human labor is expensive, it is tried to automate the migration process as much as possible. Before describing the migration process steps, ørst the target model is discussed. Then the ørst step in the migration, the node computation, is described. This is a computational geometry iproblem driven by tolerances and the quality (accuracy) attributes related to all input lines. Spatial data organization (clustering and indexing) is important to perform this step

eŒciently. The next step is placing additional lines to close certain topographic areas, this is done by hand. The ønal step is then classifying the areas and for this a rule-based system has been used. In some situations the rules may ønd strong suggestion for two or more area classes, which is then signaled. There may be an error in the original input data (wrong line classiøcation or text label) or there should be an additional line separating area in two areas.

When designing a new model we have to decide how the diœerent features are organized; e.g. are there diœerent layers or themes both from the users and technical perspective. Further, we still have to be able to deliver the traditional line oriented topographic map. This may cause some additional requirements for to model to be designed. In some cases lines in the original map coincide, e.g. the boundary of the road and the boundary of a building (partly coincide). In general, only one element is maintained on the original map according to a certain hierarchy: buildings, roads, water, etc. However, in some cases both overlapping lines have to be present in the output (according to contracts with our customers).

After the modeling, node computation and closing areas by hand the ønal areas can be created by computing the topology and storing the results in the database. The last step which has to be performed is classiøcation of the areas. It was decided to use a rule-based approach, because this classiøcation task seams very appropriate as it is less based on procedural knowledge, but more on declarative knowledge and heuristics:

1. the facts from the input data (line classiøcation, point symbols e.g. indicating water or road surface type, and text labels e.g. for street names or house numbers),

2. knowledge concerning the target area features (boundary composition, possible neighbors, reasonable size and shapes, etc.), and

3. rules describing the classiøcation of the target areas based on the input facts (e.g. an area enclosed by building boundaries and containing a house number will probably be a main building). Another motivation for choosing a rule-based approach is that it is very Æexible and can be adjusted to the provincial diœerences which exists within the input data in the Netherlands.

The ørst results of the area classiøcation are very promising. In total 19 diœerent test regions were used (from 3 diœerent provinces) and were also classiøed by hand. About 90% of the areas were classiøed in the same way, the 10% diœerences were analyzed:

1. 4-5% of the manual classiøcation was wrong;

2. 4-5% of the rule based classiøcation was wrong (classiøcation did not consider the complex conøgurations, the input facts were incomplete, and the classiøcation did also not use ιoutsideյ knowledge);

3. 0.5-1% of the input facts were errors.

The time required by manual classiøcation varies a lot, but is on the average about six hours. As the time required for the rule based classiøcation is on the average six minutes, the gain is quite signiøcant.

Supporting Multi-Layer Map Overlay and Shared Geometry Management in a GIS

Jan W. van Roessel
ESRI

Map overlay is often naively represented as a two at-a-time combination of a "red" and "green" layer, where the output polygons are the intersected polygons of both layers. Geometry libraries commonly implement two-at-a time operations on spatial features, such as the intersection or union of two polygons. While some problems in map overlay can be solved with these operators, other problems that involve the topology of a map cannot. Maintaining the topology among features involves making simultaneous changes to groups of features. For a polygonal tiling of the plane, changes in one polygon must always be reÆected in the surrounding polygons. Map overlay with line segment cracking and point clustering is best performed using multiple features simultaneously and multi-layer rather than two-at-a-time processing is preferred as well. In this paper we look at the larger picture and discuss the various map overlay, topological structuring and topological relation functions that are all performed by the same underlying overlay processor. We also describe a "topology engine" that has been constructed with the map overlay processor for the support of object oriented functions.

For a reference see for instance my paper:
"The Vector Overlay Puzzle: Where Do the Pieces Fit?" in ɿ*Advanced Geographic Data Modelling*" Edited by Martien Molenaar and Sylvia De Hoop Netherlands Geodetic Commission, Publications on Geodesy, New Series No. 40.

Using Graph Layout to Visualize Train Interconnection Data

Dorothea Wagner
Universitt Konstanz
Fakultt fr Mathematik und Informatik
This is joint work with Ulrik Brandes.

We are conerned with the problem of visualizing interconnections in railroad systems. The real-world systems we have to deal with contain connections of thousands of trains. To visualize such a system from a given set of time tables a so-called train graph is used. It contains a vertex for each station met by any train, and one edge between every pair of vertices connected by some train running from one station to the other without halting in between.

In visualizations of train graphs, positions of vertices are predetermined, since each station has a given geographical location. If all edges are represented by straight-lines, the result is visual clutter with many overlaps and small angles between pairs of lines. We here present a non-uniform approach using diœerent representations for edges of distinct meaning in the exploration of the data. Only edges of certain type are represented by straight-lines, whereas so-called transitive edges are rendered using Bezier curves. The layout problem then consists of placing control points for these curves. We transform it into a graph layout problem and exploit the generality of random øeld layout models for its solution.

A Combinatorial Framework for Map Labeling

Frank Wagner
Freie Universitt Berlin
joint work with Alexander Wolœ

The general label-placement problem consists in labeling a set of features (points, lines, regions) given a set of candidates (rectangles, circles, ellipses, irregularly shaped labels) for each feature. The problem arises when annotating classical cartographical maps, diagrams, or graph drawings. The size of a labeling is the number of features that receive pairwise non-intersecting candidates. Finding an optimal solution, i.e. a labeling of maximum size, is NP-hard. We present a combinatorial framework to attack the problem in its full generality. The key idea is to separate the geometric part from the combinatorial part of the problem. The latter is captured by the conÆict graph of the candidates. We present a set of rules that simplify the conÆict graph without reducing the size of an optimal solution. Combining the application of these rules with a simple heuristic yields near-optimal solutions. We illustrate this framework at the problem of labeling point sets with axis-parallel rectangles as candidates, four per point. We do this in such a way that it becomes clear how our concept can be applied to other cases. We study competing algorithms and do a thorough empirical comparison. The new algorithm we suggest is fast, simple and eœective.
More information can be found at `http://www.inf.fu-berlin.de/map-labeling/general`
There is a map-labeling bibliography at `http://www.inf.fu-berlin.de/map-labeling/bibliography`

Map Generalization: Challenges and Prospects

Robert Weibel
Universitt Zrich
Geograøsches Institut

The generalization of maps and spatial data is taken as an example of a key process of cartography and spatial modeling to discuss some of the challenges that computational cartography is facing today. First, the major factors deøning the problem domain of autoamted map generalization are reviewed: The three components available to model a spatial entity (space, theme, and time); the diœerences of deøning optimality in computational cartography vs. in cartography; the diœerences between dealing with data vs. dealing with graphics; and the four classes of generic cartographic processes (selection/elimination, placement, transformation/deformation, and characterization). Next, the external challenges that computational cartography and generalization are subject to are reviewed: The current trend towards uncertainty handling (vs. the ıtraditionalɉ view of crisp objects); the move towards multiple representations and integrated multiscale databases; and the trend towards on-demand mapping. The remainder of the talk deals with the identiøcation of speciøc challenges for map generalization in the following priority areas: Database generalization and multiscale DB creation; contextual generalization algorithms; measures for characterization and assessment; and experimentation and knowledge acquisition.

Labeling Rivers Nicely

Alexander Wolœ
Universitt Greifswald
joint work with Lars Knipping, Marc van Kreveld, Tycho Strijk, and Pankaj
K. Agarwal

Labeling maps consists of placing labels of point, linear, and area features appropriately. In this paper we focus on labeling polygonal chains, such as rivers or streets. We list the requirements of high-quality line labeling and divide them into two categories, *hard* and *soft* constraints. We propose an algorithm that produces a candidate strip along the input polyline; then we use an evaluation function to ønd one or several good label placements within the strip. The strip has the same height as the given label, consists of rectangular and annular segments, and fulølls the hard constraints. Within the strip, the evaluation function ønds optimal label placements according to one or a combination of several soft constraints. Our algorithm is conceptually simple. In the worst case, it runs in $O(n^2)$ time, where n is the number of points of the polyline. The algorithm requires linear storage. We analyzed our algorithm by applying it to synthetic as well as real-world data.
More information can be found at `http://www.inf.fu-berlin.de/map-labeling/lines`
There is a map-labeling bibliography at `http://www.inf.fu-berlin.de/map-labeling/bibliography`

Processing Geometric Line Data by Using Quadtree

Hongguang Yang
SICAD Geomatics

Consider a quadtree which is constructed as following: At the 0-th level (the root) the quad points to its four neighbor edges (all of them are also at the 0-th level) and each edge again has two points to the beginning and ending nodes. At the 1-th subdividing level, the root quad points to each of its four sub-quads. Each sub-quad points not only back to the root quad, but also to its four neighbor edges (all of them are at the 1-th level). These edges of the 1-th level are pointed to either by their root edge or by the root quad, and point back to them too. They also point to nodes of the 1-th level.

The subdividing and pointing process continues recursively for approximating a given line within the root quad, until the required resolution has been reached. During the process some quads have to be subdivided and others not, depending on if the line approximation will use the subdivided quadtree edges or not (modiøed Bresenham algorithm). At the end the n-th level subdividing will be completed where n = (int)ln(L/R) with L=length of the root quad and R=resolution. A ıpyramid quadtreej with linked edges and nodes at all subdividing levels will be generated.

For each level of the pyramid quadtree there is one approximation of the line by a set of equal sized edges at this level, in other words for diœerent geometric resolutions. These approximating edges can be extracted very fast and eŒciently. The achieved result can be seen as a ørst step to generalize (simplify) polylines algorithmically by using pyramid quadtree.

Industrial Presentation SICAD: Component Technique

Hongguang Yang
SICAD Geomatics

A short introduction of SICAD Geomatics Company and SICAD GIS Product family was made.
The ıcomponent techniqueɟ was characterized from diœerent points of view, i.e. application, abstract concept and information technology. The Microsoft COM implementation was explained as sophisticated technology and the SICAD millennium edition based on this technology has been showed by examples.

Contact information

Pankaj Kumar Agarwal

Duke University
Computer Science Dept.
LSRC Bldg.
Box 90129
NC 27708-0129 Durham (USA)
Tel: +1-919-660-6540
Fax: +1-919-660-6519
e-Mail: pankaj@cs.duke.edu
URL: `http://www.cs.duke.edu/~pankaj`

Natalia V. Andrienko

GMD
Forschungszentrum Informationstechnik
Schlo Birlinghoven
D-53754 St. Augustin (D)
Tel: +49-2241-142-329
Fax: +49-2241-142-242
e-Mail: gennady.andrienko@gmd.de
URL: `http://allanon.gmd.de/and/`

Mathieu Barrault

Universitt Zrich
Geograøsches Institut
Winterthurerstr. 190
CH-8057 Zrich (CH)
Tel: +41-1-635-6534
Fax: +41-1-635-6848
e-Mail: brrault@geo.unizh.ch
URL: `http://www.geo.unizh.ch/~barrault/`

Antoinette Beckert

Concept Software GmbH
Monumentenstr. 35
D-10829 Berlin (D)
Tel: +49-30-7809-9113
Fax: +49-30-7809-9111
e-Mail: beckert@concept-software.de
URL: `http://www.concept-software.de/`

Joachim Bobrich

Universitt Hannover
Institut fr Kartographie
Appelstr. 9a
D-30167 Hannover (D)
Tel: +49-511-762-2472
Fax: +49-511-762-2780
e-Mail: joachim.bobrich@ifk.uni-hannover.de
URL: `http://www.ifk.uni-hannover.de/`

Martin Breunig

Universitt Bonn
Institut fr Informatik IV
Rmerstr. 164
D-53117 Bonn (D)
Tel: +49-228-73 45 35
Fax: +49-228-73 43 82
e-Mail: martin@cs.uni-bonn.de
URL: `http://www.cs.uni-bonn.de/~martin/`

Marc-Olivier Briat

Hemispheres - Paris
25-27 Rue de Tolbiac
F-75013 Paris (F)
Fax: +33-2-37 48 71 69
e-Mail: mobriat@aol.com

Dirk Burghardt

Maptech AG
Ebenaustr. 10
CH-6048 Horw (CH)
Tel: +41-41-349-2312
Fax: +41-41-349 2324
e-Mail: d.burghardt@maptech.ch
URL: `http://www.maptech.ch`

Robert Cromley

University of Conneticut
Dept. of Geography
CT 06269-2148 Storrs (USA)
Tel: +1-860-486-2059
Fax: +1-860-486-1348
e-Mail: cromley@uconnvm.uconn.edu

Paul Dur

Barco Graphics
Cartogpraphy Systems
Tramstraat 69
B-9052 Gent (B)
Tel: +32-9-2169-237
Fax: +32-9-2169-825
e-Mail: paul.dure@barco.com
URL: `http://www.barco.com/graphics/cartography`

Alon Efrat

Stanford University
Dept. of Mathematics
Gates 375
CA 94305-2125 Stanford (USA)
Fax: +1-650-723-0033
e-Mail: alon@cs.stanford.edu

Andrew Frank

Technische Universitt Wien
Inst.fr Geoinformatik
Gusshausstrae 27-29
A-1040 Wien (A)
Tel: +43-1-58801-12700
Fax: +43-1-58801-12799
e-Mail: frank@geoinfo.tuwien.ac.at

Chris Gold

Universit Laval
Centre de Recherche en Gomatique
Pavillon Casault
St. Foy
G1K 7P4 Qubec (CDN)
Tel: +1-418-656-338
Fax: +1-418-656-7411
e-Mail: christopher.gold@scg.ulaval.ca

Annette Halbhuber

Transport- Informatik u. Logistik-Consulting GmbH
EVA - Fahrplanzentrum
Klner Str. 26
D-60327 Frankfurt (D)
Tel: +49-69-265-25148
Fax: +49-69-265-25354
e-Mail: annette.halbhuber@tlc.de

Jean-Francois Hangouet

IGN/COGIT
DT, M306
2 Ave. Pasteur
F-94165 Saint Mande Cedex (F)
Tel: +33-1-43 98 81 71
Fax: +33-1-43 98 81 71
e-Mail: Jean˙Francois.Hangouet@ign.fr
URL: `http://www.ign.fr`

Paul Hardy

Laser-Scan Ltd.
Cambridge Science Park
Milton Road
CB4 0FY Cambridge (GB)
Tel: +44-223-420-414
Fax: +44-223-420-044
e-Mail: paul@lsl.co.uk
URL: `http://www.laser-scan.com/`

Martin Heller

Universitt Zrich
Geograøsches Institut
Winterthurerstr. 190
CH-8057 Zrich (CH)
Tel: +41-1-302-3139
e-Mail: heller@geo.unizh.ch

Klaus Hinrichs

Westflische Wilhelms-Universitt Mnster
FB 10 Informatik
Einsteinstr. 62
D-48149 Mnster (D)
Tel: +49-251-833-3752
Fax: +49-251-833-3755
e-Mail: hinrichs@math.uni-muenster.de
URL: `http://www.uni-muenster.de/math/inst/info/u/khh/`

Lorenz Hurni

ETH Zrich
Institut fr Kartographie
ETH Hnggerberg
CH-8093 Zrich (CH)
Tel: +41-1-633-3033
Fax: +41-1-633-1153
e-Mail: hurni@karto.ethz.ch
URL: http://www.karto.ethz.ch/

Michael Kaufmann

Universitt Tbingen
Wilhelm-Schickard-Institut fr Informatik
Sand 13
D-72076 Tbingen (D)
Tel: +49-7071-2977-404
Fax: +49-7071-67540
e-Mail: mk@informatik.uni-tuebingen.de
URL: http://www-pr.informatik.uni-tuebingen.de

Ajay Mathur

Maptech AG
R&D Manager
Ebenaustr. 10
CH-6048 Horw (CH)
Tel: +41-41-3492323
Fax: +41-41-3492324
e-Mail: ajay@maptech.ch
URL: http://www.maptech.ch

Martien Molenaar

Intern. Institute for Aerospace Survey and Earth Science
Division of Geoinformatics and Spatial Data Acquisition
Hengelosestraat 99
P.O. Box 6
NL-7500 AA Enschede (NL)
Tel: +31-53-4874269
Fax: +31-53-4874335
e-Mail: molenaar@itc.nl
URL: http://www.itc.nl

Corinne Plazanet

EPFL
Lab. de Bases de Donnes
CH-1015 Lausanne (CH)
Tel: +41-21-693-5212

Fax: +41-21-693-5195
e-Mail: corinne.plazanet@epÆ.ch
URL: `http://lbdsun.epfl.ch/~corinne/`

Alan Saalfeld

Ohio State University
Dept. of Civil and Environ. Eng & Geodetic Science
Hitchcock Hall 470
2070 Neil Ave.
OH 43210-1275 Columbus (USA)
Fax: +1-614-292-2957
e-Mail: saalfeld.1@osu.edu

Jrg-Rdiger Sack

Carleton University
School of Computer Science
Herzberg Bldg. 5th Æoor
1125 Colonel By Drive
ON-K1S 5B6 Ottawa (CDN)
Tel: +1-613-520-43 61
Fax: +1-613-520-43 34
e-Mail: sack@scs.carleton.ca
URL: `http://www.scs.carleton.ca/~sack`

Monika Sester

Universitt Stuttgart
Institut fr Photogrammetry
Geschwiester-Scholl-Str. 24 d
D-70174 Stuttgart (D)
Tel: +49-711-121-3384
e-Mail: monika.sester@ifp.uni-stuttgart.de
URL: `http://www.ifp.uni-stuttgart.de/private/Sester/`

Jack Snoeyink

University of North Carolina at Chapel Hill
Dept. of Computer Science
Campus Box 3175
Sitterson Hall
NC 27599-3175 Chapel Hill (USA)
Tel: +1-919-962-1969
Fax: +1-919-962-1799
e-Mail: snoeyink@cs.ubc.ca
URL: `http://www.cs.une.edu/~snoeyink`

Tycho Strijk

Utrecht University
Dept. of Computer Science
Padualaan 14
Postbus 80.089
NL-3584 CH Utrecht (NL)
Fax: +31-30-251-3791
e-Mail: tycho@cs.uu.nl
URL: `http://www.cs.uu.nl/people/tycho/`

Jan Vahrenhold

Westflische Wilhelms-Universitt Mnster
FB 10 Informatik
Einsteinstr. 62
D-48149 Mnster (D)
Tel: +49-251-83-38444
Fax: +49-251-83-33755
e-Mail: jan@math.uni-muenster.de
URL: `http://wwwmath.uni-muenster.de/cs/u/jan/`

Steven van Dijk

Utrecht University
Dept. of Computer Science
Padualaan 14
Postbus 80.089
NL-3584 CH Utrecht (NL)
Fax: +31-30-251-3791
e-Mail: steven@cs.uu.nl
URL: `http://www.cs.uu.nl/~steven/`

Marc van Kreveld

Utrecht University
Dept. of Computer Science
Padualaan 14
Postbus 80.089
NL-3584 CH Utrecht (NL)
Tel: +31-30-2534119
Fax: +31-30-2513791
e-Mail: marc@cs.uu.nl
URL: `http://www.cs.uu.nl/~marc`

Peter van Oosterom

Dutch Cadastre
Waltersingel 1
P.O. Box 9046
NL-7300 GH Apeldoorn (NL)

Tel: +31-55-5285163
e-Mail: oosterom@kadaster.nl
URL: `http://ooa.kadastern.nl`

Jan W. van Roessel

ESRI
380 New York Street
CA 92373 Redlands (USA)
e-Mail: jvanroessel@esri.com

Dorothea Wagner

Universitt Konstanz
Fakultt fr Mathematik u. Informatik
D 188
D-78457 Konstanz (D)
Tel: +49-7531-88-2893
Fax: +49-7531-88-3577
e-Mail: Dorothea.Wagner@uni-konstanz.de
URL: `http://www.fmi.uni-konstanz.de/`

Frank Wagner

Freie Universitt Berlin
FB Mathematik und Informatik
Takustr. 9
D-14195 Berlin (D)
Tel: +49-30-838-75159 /75103
Fax: +49-30-838-75109
e-Mail: wagner@inf.fu-berlin.de
URL: `http://www.inf.fu-berlin.de/~wagner/`

Robert Weibel

Universitt Zrich
Geograøsches Institut
Winterthurerstr. 190
CH-8057 Zrich (CH)
Tel: +41-1-635-5152
Fax: +41-1-635-6848
e-Mail: weibel@geo.unizh.ch
URL: `http://www.geo.unizh.ch/~weibel/`

Alexander Wolœ

Universitt Greifswald
Institut fr Mathematik und Informatik
Jahnstr. 15 A
D-17487 Greifswald (D)
e-Mail: awolœ@mail.uni-greifswald.de

URL: `http://www.inf.fu-berlin.de/~awolff/`

Hongguang Yang

SICAD Geomatics
Otto-Hahn-Ring 6
D-81739 Mnchen (D)
Tel: +48-89-636-44282
Fax: +48-89-636-43939
e-Mail: hongguang.yang@sicad.de