Some Requirements for Geographic Information Systems: A Photogrammetric Point of View[1]

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Abstract

Some requirements which an ideal geographic information system (GIS) must meet to cope with the challenges of the future are described. We look at data modeling, the integration of geographic information science and photogrammetry, update and refinement of a geospatial database, and data integration. We claim that data modeling needs to be carried out in 3D based on a topologic data structure with the possibility for incorporating change. Photogrammetric operations such as the generation of digital terrain models or the manual and automatic acquisition of vector data from imagery should be considered as modules of future GIS, which should also have efficient mechanisms for incremental updating and versioning. Finally, the integration of all types of data should be possible, e.g., various vector data sets as well as DTMs and images.

We illustrate the requirements with the help of three examples, one describing data acquisition and modeling in an interdisciplinary project, one dealing with quality control and update using imagery, and the last one presenting an algorithm for the integration of a 2D data set and a DTM.

This paper discusses GIS from a photogrammetric point of view with an emphasis on imaging and data acquisition. While we believe that the discussed requirements are vital for the development of GIS, we are aware of the fact that other issues such as database design, software architecture, visualization, geospatial data infrastructure, and web mapping, only briefly mentioned or not discussed at all in this paper, are of similar importance for the field.

Introduction

Geospatial information, i.e., information about objects and facts with spatial reference, is an essential part of the national and international infrastructure for the information society. It is estimated that some 80 percent of our daily decisions rely on geospatial information. Geographic information systems (GIS), which allow for the acquisition, storage, manipulation, analysis, visualization, and dissemination of geospatial information are therefore of prime interest to society at large. This implicit definition of a GIS follows the well-known IMAP (input, management, analysis, presentation) model, but adds the aspect of dissemination of the information, because the latter has become a major focus of research, development, and economic activity.

GIS have received major attention over recent years. There are various breeds of commercially available GIS which can broadly be classified into (1) complete GIS with the full range of functionality, (2) desktop GIS with a reduced functionality mainly used for visualizing existing data and simple analysis, (3) GIS database servers which are essentially spatial database management systems with a user interface and extensions for handling geometric data, and (4) web GIS which allow for visualization, disseminating, and some analysis over the web based on a client-server architecture. We consider the second to the fourth class as reduced versions of the first one and will not differentiate between the different classes in the remainder of this paper. We will also not try to give an overview of existing commercial systems and their advantages and limitations. In contrast, we will look at an ideal system and discuss some of the extensions which we feel the user will require in a future GIS. It should be noted that we do not believe that one single system will, or needs to, have all the mentioned extensions implemented, but rather that we will see more specialized systems fulfilling one or the other requirement.

This paper discusses GIS from a photogrammetric point of view. It should thus not come as a surprise that imagery plays a significant role, and we emphasize data acquisition rather than analysis, visualization, and dissemination of geospatial data. After having discussed modeling aspects of geo-objects in the second section, we elaborate on the integration of GIS and imagery and thus the integration of photogrammetry and geographic information science. Imagery also plays an important role in the fourth section in which we deal with updating. The fifth section is concerned with data integration, and we briefly touch on interoperability and standards. In the sixth section we illustrate the rather theoretical material presented before with the help of three examples, before giving a summary and some conclusions.

The reader will miss a number of important topics in geographic information systems in this paper. These include database issues (object-oriented database design, efficient access mechanisms, database consistency, query languages, federated databases, data security, etc., for which see Laurini (1998), Gröger (2000), and Breunig (2001)), software architecture (Woodsford, 2001), issues related to visualization (3D, dynamic, and interactive visualization, for which see Buziek (2001), Kraak (2002), and Nebiker (2003)), and the connection of GIS and the web (web-mapping, geo-marketing, etc.). As important as these topics are for the ideal GIS of the future, in the interest of space, a discussion of these issues is beyond the scope of this paper.

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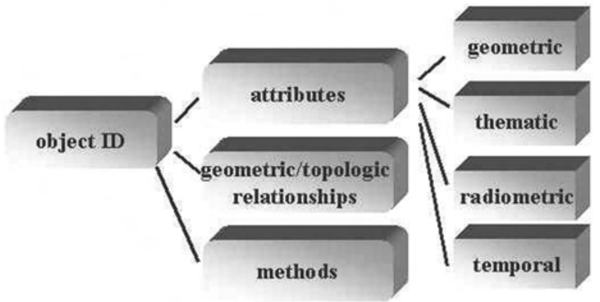

Figure 1. On the definition of a geo-object.

Modeling Geo-Objects

We want to start the discussion in this section with the observation that, in most cases, we view the world as being composed of objects. We use the term "object" according to the *object modeling technique* (Rumbaugh *et al.*, 1991). Geo-objects are objects with a spatial and possibly also a temporal reference. Each object has a unique identity and is described by geometric, thematic, radiometric, and temporal attributes (radiometric attributes are needed to describe the appearance in the images that enable image analysis and realistic rendering), as well as geometric/topologic relationships to objects, and their behavior in terms of valid methods (see also Figure 1). The object "knows" which methods are valid, and how these are carried out. It can be classified according to its description (attributes, relations, behavior); individual objects are instances of a class or concept. The principle of inheritance allows for common use of attributes and methods between classes within a hierarchical is_a relationship. Access to the objects occurs only through message passing, an approach referred to as encapsulation. This definition of an object differs from that sometimes found in geographic information science, where the object behavior is not always considered part of the object and needs to be described separately.

In general, we can distinguish two different methods to describe geospatial information: the *field-based model* and the *object-based model*[2]. The field-based model contains continuous information for the considered scene. Examples are a digital terrain model (DTM) or a temperature field; in essence, information is available everywhere in the considered region. Often, information is given at node points; thus, an interpolation function (for a good example of a method, see above) needs to be specified to compute values at an arbitrary position. In the field-based model, information is commonly represented as a grid, but triangular irregular networks (TIN) also belong to this group. In contrast to the field-based model, the object-based model describes discrete entities by their location, shape, size, and further attributes. Buildings, roads, trees, etc., fall into this group.

For a long time, information described in one or the other model was managed independently. DTMs, for example, have traditionally been collected and managed separately from the two-dimensional object information. Today, however, there is an increasing demand for 2.5D and 3D geospatial information. This demand was also expressed during a workshop conducted by EuroSDR (European Spatial Data Research, formerly known as OEEPE, the European Organisation for Experimental Photogrammetric Research)(OEEPE, 2001a).

Topologic data structures are particularly important for GIS analysis, because they make information about spatial relationships between objects explicit and thus extend the query space, i.e., the set of questions which can be answered by the system without heavy algorithmic computations. A topologic data structure has also further advantages; see, e.g., van Oosterom *et al.* (2002). Therefore, topology plays a major role in modeling geo-objects. In two dimensions, node-arc data structures based on graph theory have been developed (e.g., the formal data structure for a single-valued vector map by Molenaar (1989; 1998); see also Gröger (2000)). Point features are geometrically described by nodes, line features by arcs, and area features by a connected set of closed arcs (also called chains) representing the boundary of the area.

With the increasing interest in 3D and also in time, e.g., from geology or urban information systems, the two-dimensional data structures were extended, and 3D GIS became an active field in research and development (e.g., Raper and Kelk, 1993). 3D geospatial data modeling can be distinguished into different types, namely, spatial enumeration or voxels (volume elements), tetrahedral networks (TEN), constructive solid geometry (CSG), and boundary representations (b-rep). Voxels, CSG, and b-rep are illustrated in Figure 2.

Voxels are an extension of a 2D raster and contain object information only implicitly. Extensions comprise octrees, which is the 3D variant of the well-known quadtrees. A TEN is an extension of a TIN into the third dimension. Tetrahedrons are the basic primitive of a TEN in the same way as triangles are the basic primitive of a TIN. TEN are employed in applications where arbitrarily shaped objects have to be dealt with, e.g., in geology. They are, however, less suited for regular objects (see, e.g., Shi *et al.* (2003)). Octrees and TEN are both

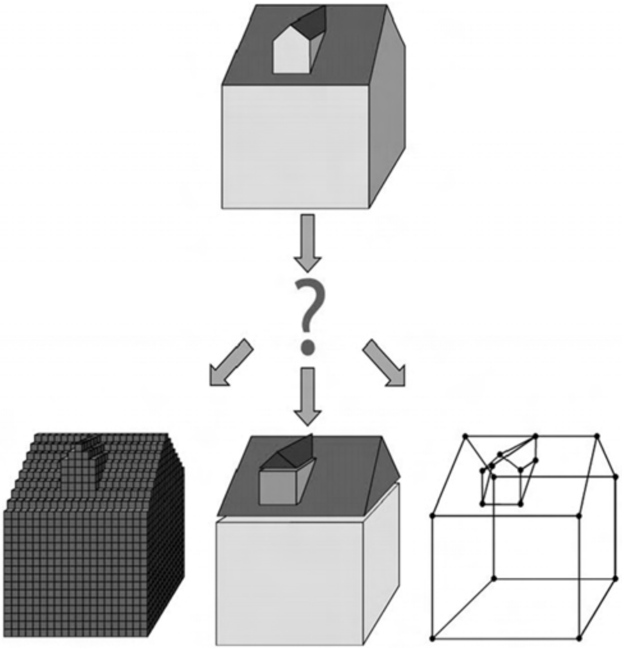

Figure 2. Three possibilities for 3D data structures of buildings: voxels (left), constructive solid geometry (center), boundary representation (right); from Pfund (2002).

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[2] Note that both models can be implemented according to the object-oriented modeling technique. Also, as already pointed out by Goodchild (1990), the main question in this regard is not whether one model is better than the other, but which model is best for which problem.

related to the field-based models and can also be combined into one hybrid data structure (Li and Li, 1996).

CSG combines basic geometric 3D primitives (cubes, prisms, tetrahedrons, spheres, etc.) by Boolean operations. It is not always easy to construct a complicated object from the set of primitives, and such a construction may not be unique. Also, there are limitations with respect to the obtainable degree of detail. CSG models are successfully being used for photogrammetric data acquisition of buildings; see, for example, Gülch *et al.* (1999).

In the b-rep data structure a 3D object is described by the surface patches which form its boundary. Often these boundaries are simple geometric elements such as planar patches. Alternatively, the patches can be described by piecewise parametric polynomial functions allowing for curved patches, e.g., non-uniform rational B-splines (NURBS) (Raper and Kelk, 1993). The b-rep data structure is popular for 3D CAD systems and some GIS. It has been employed for photogrammetric building extraction (Rottensteiner, 2001), it is often used in computer graphics for visualization purposes, and it is also incorporated into the virtual reality modeling language (VRML). A unique b-rep can be derived from a CSG model, but the inverse is not possible because, in general, the CSG description is not unique.

Adding efficient query capabilities as additional requirements for 3D modeling of geo-objects, topologic data structures are also needed in the third dimension. The b-rep data structure is the natural extension of the node-arc structure into 3D. In this case, point features are represented by nodes, line features by arcs, surface features by faces, and three-dimensional volume features, also called solids, by a set of connected faces. First suggestions for a 3D topologic data structure were made by Molenaar (1990; see also the overview by Fritsch (1996)). More recent developments are contained in Losa and Cervelle (1999), Pfund (2002), Ramos (2002), Zlatanova *et al.* (2002), and Shi *et al.* (2003). The authors present various ways to set up topologic data structures in 3D; Shi *et al.* (2003) also compare different possibilities and discuss the pros and cons of the individual approaches. In general, the type of objects to be modeled and the different queries to be asked should be primarily considered in the choice for an appropriate data structure.

As far as *modeling time and change* in GIS is concerned (see also Wachowicz (1999)), a distinction can be made between approaches connecting different epochs by so called state transition diagrams, and approaches which explicitly model the process itself. The first approach describes different states of an object; changes from one epoch to the next can be restricted by setting conditions on the possible state transitions. The description of the objects needs to be augmented by temporal attributes such as a relative or absolute starting point and a life cycle (see, e.g., Zipf and Krüger (2001) for a description of a 3D temporal data structure). This approach is useful for changing scenes in which individual snapshots are more important than the dynamic description of change itself. It is interesting to note that the same concept has also been employed in multitemporal image analysis (Growe, 2001; Pakzad, 2001). The second approach describes change explicitly as a function of time. Such an approach is useful for changes in which the dynamics are of prime importance; individual snapshots can then be generated by interpolation.

As soon as time and change are modeled, one must have a possibility for the geo-object to have *multiple representations* (Sester, 2001). Here, the object-oriented paradigm comes into play again, because an object with a unique identity can have different descriptions in different environments. Similar mechanisms are needed in order to represent objects across multiple aggregation levels (scales), a task which needs to be solved in generalization. One can also combine aggregation and time in order to model changing geo-objects across different aggregation levels.

From the discussions in this section, we can formulate our first requirement for an ideal geographic information system: for describing the geospatial information, the object-oriented modeling technique should be used, the system should have a topologic data structure, and it should be possible to model and query 3D geo-objects which can change over time and scale with multiple representations per object. Currently available systems are rather far away from this ideal system, especially in terms of topological data structures for analysis in 3D and time, but research efforts are under way to meet the mentioned requirements one after the other.

GIS and Imagery

It is well known that the geospatial information constitutes the most valuable part of any GIS, partly because of the high cost involved in data acquisition and update, but also because of the long life-cycles as compared to GIS hardware and software. A particularly important issue is the task of populating the GIS databases with the core geospatial information. Core geospatial information, also known as core GIS data, base data, or framework data, is usually considered to constitute the cadastral and the topographic information which serves as a common foundation for application data in different disciplines and is usually provided by National Mapping Agencies.

In this chapter we elaborate at some length on the role of images within a GIS. Their role is threefold: images are a prime source for acquiring geospatial information, images serve as a backdrop to convey to the user information not explicitly available in the GIS, and images are indispensable for realistic rendering of a scene. Here we focus on using images to derive geospatial information.

For many decades photogrammetry and remote sensing have proven over and over again their ability to meet the mentioned requirements for geospatial information (e.g., Englisch and Heipke, 1998). Therefore, photogrammetry and remote sensing provide the primary technology for core geospatial information acquisition and update. The Ordnance Survey of Great Britain, for example, estimates that some 50 percent of the information for their mapping products will come from photogrammetric imagery in the future (Murray, 2001, personal communication), and similar numbers can be heard from other National Mapping Agencies.

In the past, photogrammetry and remote sensing on the one hand, and geographic information science on the other hand, were distinct disciplines, being mainly connected through data transfer from imagery to the GIS database. The increasing coherence between acquisition, update, and further use of the information, however, had significant consequences for their relationship. Already more than ten years ago, Dowman (1990) characterized a photogrammetric workstation as being an active window into the 3D GIS database, and two years later, Sarjakoski and Lammi (1992) laid down requirements for a stereo workstation in the GIS environment. Today, besides a bi-directional link to store information acquired from the images, but also to use existing GIS data as prior information for updating, a trend for a complete integration can be observed. In this sense, photogrammetry and remote sensing can be described as a three-dimensional data acquisition module of GIS, using multisensor, multispectral, and multitemporal images, including data from laser scanners and interferometric synthetic aperture radar (InSAR) as primary data sources. For orientation purposes, the corresponding sensor system is equipped with a GPS (Global Positioning System) receiver, an IMU (inertial measurement unit), and (at present still mandatory, but in the

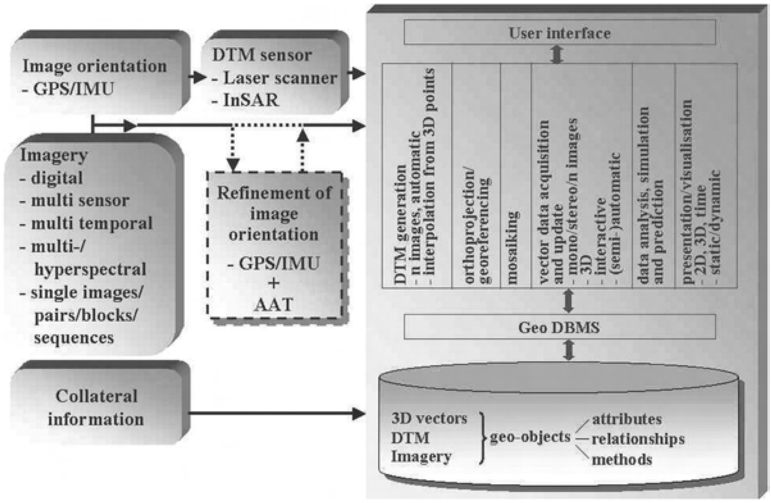

Figure 3. Concept of an integrated GIS and photogrammetry system.

future perhaps optional) software for AAT (automatic aerial triangulation) to refine the directly measured exterior orientation of the images; collateral information, such as the coordinates of ground control points (GCPs) can be used optionally. In essence, the results of the sensor system are oriented images, available immediately after data acquisition, and a dense set of 3D points describing the object surface. All tasks connected with further data processing, may they be termed photogrammetric or not, can then be considered as GIS modules working on a common database.

Figure 3 depicts such a conceptual integration of photogrammetry, remote sensing, and geographic information science. GIS modules for data processing comprise the generation of DTMs, ortho-images, and ortho-image maps; the acquisition of vector data; and also the analysis and visualization of the data. Image analysis tools (e.g., Gülch, 2000; Heipke *et al.*, 2000; Liedtke *et al.*, 2001) fit into this scheme as additional GIS modules.

To summarize this section, a modern geographic information system needs to be able to cope with imagery and contain modules for acquisition, update, and processing of 3D geo-objects from imagery, traditionally considered as part of a digital photogrammetric workstation.

First steps towards realizing such a GIS have been undertaken by the major competitors in the field, for example, by combining the ERDAS Imagine stereo analyst from Leica Geosystems with ESRI's ArcGIS; Socet set of BAE with the Lamps2 database from Laser Scan (Edwards *et al.*, 2000); the ImageStation from Z/I Imaging with Intergraph's Geomedia; or the Finish ESPA System with AutoCAD, MicroStation, or Smallworld.

Update and Refinement of Geospatial Information

Updating[3] refers to the task of comparing two data sets (one representing the current state of a database, the second one representing some more recently generated data set) with the aim to detect and capture changes, and to import these changes into the database. In our context, the database is of course the GIS database, and the second data set can take the form of imagery, results from a field survey, or data acquired from some other source. In general, it will be necessary to use multiple data sources for updating a GIS database. By means of updating, the database is constantly adapted to the changes of the landscape. Updating is thus closely related to temporal issues in GIS. Updating tasks which need to be supported are the creation, deletion, splitting, and merging of objects, and the modification of its geometric, topologic, thematic, and temporal description. Due to the demands of a number of applications—we only mention car navigation as a very obvious example—the updating cycles of the past amounting to various years are not acceptable for today's GIS.

Refinement is the process of increasing the quality of existing data in terms of geometric, topologic, thematic, and temporal information. In particular, the removal of GPS selective availability has led to the possibility to quickly detect geometric inaccuracies, resulting in a number of projects, especially in the U.S., to geometrically improve existing geospatial information (e.g., Woodsford, 2001). Refinement also includes the extension of the thematic description in terms of additional attributes.

As mentioned, updating and refinement both need *quality descriptions* for the existing and the newly acquired geospatial information in order to be able to actually improve the data quality. Such descriptions are also needed for many applications because the results of an analysis often depend on the quality of the input information. CEN (Commitée Européen de la Normalisation) developed the model of ISO 19113 defining Meta Data Standards to describe data quality. The model involves the quality criteria for positional accuracy, thematic accuracy, completeness, logical consistency, and temporal accuracy (see also Joos (2000)). Whereas a description of geometric quality based on statistical concepts (e.g., standard deviation of the position) is relatively straightforward, a description of the other criteria, and also of the topologic quality, is more complex (see Gröger (2000) for a discussion on logical database consistency, and Winter (1996) and Raggia (2000) for handling of topologic uncertainty). An additional problem is the propagation of uncertainty in the analysis processes (Glemser, 2000).

Not only from a photogrammetric point of view is updating from images most attractive. The challenge here is to automate all three tasks; change detection, data capture, and import into the database. One example for GIS updating from images will be given later, while another one is the ATOMI

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[3] In this text we use the term "updating" as a synonym for "revision."

project[4] of ETH Zürich and the Swiss Federal Office of Topography (Eidenbenz *et al.*, 2000; Niederöst, 2001; Zhang *et al.*, 2001). It should be noted, however, that both projects are limited to the first two tasks (detection and data capture).

The import into the database (e.g., Woodsford, 1996) is also a challenging task. Two important concepts for the update of geospatial information are *incremental update and versioning* (Cooper and Peled, 2000). A methodology for updating geographic databases using map versions is given in Peerbocus *et al.* (2002). Users often link the core geospatial information to some application data of their own and thus create value-added information. In order not to lose the viable links between the core data and the application data, once a new version of core data becomes available, it is mandatory to provide "change only" information. In this way, the user is able to incrementally update his own data set only in those areas where change has actually occurred. Updating is often done in parallel by different operators possibly using mobile equipment, or in distributed environments. In this case, the versioning mechanism allows giving different users exclusive write access to parts of the database and to create various spatially non-overlapping versions. In a second step these different versions have to be merged to generate a consistent new data set. Incremental updating and versioning can also be used to record a time series of events.

We can now formulate our next requirements: we want to be able to efficiently implement an automated update and refinement work flow using images and other data sources, to generate incremental update, and to obtain consistent states of the different versions of a database in an automated manner. Currently available geographic information systems still have a way to go to fulfill these requirements.

Data Integration and Interoperability

On the Need for Data Integration

In many applications the topography of the Earth's surface constitutes a common base for related data sets, but discrepancies and even disagreements often arise in mapping one and the same object. The reason is that the different data sets are typically based on different feature catalogs and have been collected for different purposes. Also, different sensors may have been used, data acquisition may have taken place at different dates, and so the quality and the resolution of the data most probably differs significantly. At the same time, geospatial analysis can often only be carried out by integrating different data sets (Devogele *et al.*, 1998). The goals of *data integration* are

- to use the existing data for various problems; the information which is not contained in one data set can be taken from another one;
- to complete and enhance the data sets thematically; for instance, from the intersection of one data set with another one, new thematic information can be derived; and
- to verify automatically the existing data regarding their quality, to correct them, or to improve their accuracy.

Data integration refers to an integration on different levels: on the semantic level, ontologies must match: when integrating roads from different data sets, it must be ensured that the meaning of "road" can be mapped from one data set to the next; on a geometric level: two geo-objects describing the same object in the real world must have the same location; and on the syntactic level: in order to carry out an integrated data analysis the various data sets must be linked in one way or another.

Integration can take place between vector and raster data (see the section on GIS and Imagery), two-dimensional vector data and DTMs, and/or different vector data sets. In the next subsection we will deal with the latter two cases.

Integration of Vector Data Sets

In general, the integration of different data sets is solved by matching techniques: objects of one data set are matched with corresponding objects of the other data set. This matching assumes that the data sets are available in comparable representations, i.e., the feature class catalogs can be mapped from one data set to the next. The actual comparison is carried out using search techniques. Matching constraints concerning the object classes (e.g., treatment of roads or water objects only) or the geometric position are typically taken into account. Also, object characteristics like form or size and relations between objects are often used; in addition, the information contained in the meta data can be exploited.

The matching problem can be solved in different ways. One of the first approaches for matching vector data sets of different sources, also called conflation, was carried out by the U.S. Bureau of Census (Saalfeld, 1988): the census data were integrated with data from the U.S. Geological Survey (USGS) with the objective to improve data quality. In many matching approaches the geometric position of the objects, as well as form parameters, are used. This is reasonable, as long as a unique matching is possible. If this is no longer the case, in addition to unary constraints, binary object characteristics, i.e., relations, can also be employed (Walter, 1997).

Conflict resolution during the matching process (solving disagreements between the different data sets) is a particularly difficult issue, and it can only be handled by defining a properly chosen optimization function based on a description of data quality (see the section on Update and Refinement of Geospatial Information).

These problems are treated on the one hand in the domain of the integration of heterogeneous data, and on the other hand when data of different scales have to be combined (van Wijngaarden *et al.*, 1997; Badard, 1999; Sester *et al.*, 1999; Sester, 2001).

Integration of 2D Data and a DTM

The real world is three dimensional, and an ideal GIS should be able to conveniently represent the major aspects of our environment. Therefore, the GIS should have capabilities to represent geospatial information in 3D or at least in 2.5D. 3D data modeling has been discussed earlier. Another facet of this issue is dealt with in this section: the *integration of a 2D data set and a DTM* of the same area, which have been built up independently.

First, we are concerned with establishing an integrated 2.5D data structure. One approach, based on triangulation, can even be traced back to the roots of the TIN concept (Peucker *et al.*, 1976). Later, other authors have picked up the topic (e.g., Pilouk and Kufoniyi, 1994; van Oosterom *et al.*, 1994; Kraus, 1995). The general idea is to integrate the object boundaries as edges into a DTM with TIN structure. As an important property of an integration process, Klötzer (1997) required that the terrain shape of the DTM-TIN should not be altered while adding nodes and edges of the 2D data. This condition prevents the quality of terrain approximation by the TIN from deteriorating during the integration process.

Various procedures for the integration task have been suggested. The approaches differ in the way they actually introduce the 2D geometry information into the TIN. Options include a sequential introduction of one node after the next, followed by the edges (Pilouk, 1996; Klötzer, 1997), hierarchical overlay (Abdelguerfi *et al.*, 1997), and the introduction of a node followed by an edge, the next node, the next edge, and so on (Lenk, 2001). Care must be taken that not only do the

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[4] ATOMI = Automated reconstruction of Topographic Objects from aerial images using vectorized Map Information.

edges of the 2D data but also the TIN edges carrying geomorphologic information remain unchanged, because otherwise the terrain shape is altered. Also, the resulting number of node points and the computational complexity should be kept to a minimum.

Another issue of the integration of 2D data and a DTM is the semantic consistency of the integrated data set. It cannot, for example, be guaranteed *a priori* that a river will actually run downhill after the integration. To give another example for the difficulties arising in semantic consistency, it is by no means guaranteed that a road cross section is flat along the whole road (as it should be), when only the road centreline and the width are available from the 2D data set. This second problem is more complex, because also attributes (in this case the road width) have to be considered during the re-computation. These problems will in general arise if the used 2D data and/or the DTM did not have the necessary geometric accuracy. In order to solve this problem, it is not sufficient to only change individual 2D data points or DTM posts, but a consistent re-computation of all the surrounding information taking into account the semantic conditions is necessary. A solution based on least-squares adjustment is presented by Koch (2003).

It should be noted that once the two data sets are integrated, they need to be considered as one common data set. Otherwise, operations such as update or integrating application data (see above) will result in inconsistencies.

Standards and Interoperability

On a more technical level, an integrated data analysis can only be carried out if the different GIS can "talk" to each other. This requirement can be translated into the need for standards. In recent research and development, much attention has been paid to the developments of such standards. Major driving forces are the OpenGIS Consortium (OGC) and the International Standards Organization Technical Committee ISO TC 211. It was realized that in order to avoid time-consuming and error-prone conversion of data between different systems, so called "interoperable geoinformation systems" should be developed.

OGC defines interoperability as the "ability for a system or components of a system to provide information portability and interapplication, cooperative process control. Interoperability, in the context of the OpenGIS Specification, is software components operating reciprocally (working with each other) to overcome tedious batch conversion tasks, import/ export obstacles, and distributed resource access barriers imposed by heterogeneous processing environments and heterogeneous data" (OGC website, www.opengis.org, last accessed 17 October 2003). Breunig (2001, p. 8) explains interoperability as the "capability to exchange functionality and interpretable data between software systems." Both definitions clearly show that interoperability is much more than data format conversion or pure exchange of data. Spatial queries are sent from one system to a second one, where the query is interpreted based on a predefined protocol. In this second system data are subsequently accessed and possibly also processed, and the result (the answer to the query, possibly including data) is sent back to the first system.

For a number of years, major efforts based on OGC's "Open Geodata Interoperability Specifications" have been undertaken to realize interoperable GIS. Especially for access across the World Wide Web, the eXtended Markup Language (XML) and its derivative for geospatial information, the Geography Markup Language (GML), are of increasing importance; see also OEEPE (2001b), Reichardt (2001), and Altmaier and Kolbe (2003).

Thus, our last requirement for modern geographic information systems is that they contain tools for data integration, and it should be an interoperable system. Currently, many system developers strive to fulfill these requirements, but some work still has to be done before interoperable systems with data integration capabilities will be state-of-the-art in GIS.

Examples

In this section we will describe a few examples to illustrate some of the issues discussed in the previous sections of the paper. The examples are drawn from current projects running at our Institute. We don't claim that these projects ideally describe each individual topic. We have selected them, because we simply know them best.

CROSSES—3D Geospatial Information for a Non-Conventional Application

CROSSES stands for CROwd Simulation System for Emergency Situations. The main objective of the project is to provide virtual reality tools for training people to efficiently respond to urban emergency situations involving human crowds. Typical urban emergency situations are, for example, a fire breaking out in the center of a city, a bomb exploding in a crowded neighborhood, or riots in a football stadium. When confronted with such situations, the reactions of people are in general very difficult to control, and the emergency plans elaborated in advance may be inefficient or insufficient. CROSSES provides training for such scenarios in a real-time simulator. The trainee, for example a policeman, is part of the scenario. His task is to react properly to an emergency situation in order to save the life of people and minimize danger. Artificial autonomous humans (avatars) move around freely in the scene. The avatars are implemented as autonomous agents, and their individual behavior is not predefined. This is a major difference from standard computer games. Each avatar has an individual behavior coded in rules; collectively, the avatars constitute the crowd. They can run away from a fire, panic in one way or another, etc. CROSSES also has a sound modeling subsystem to increase the perception of realism during the training. The different components are depicted in Figure 4, and a snapshot from one of the scenarios can be seen in Figure 5.

Realism in the simulation is necessary to the degree that the trainee can recognize the surroundings, so that he can activate his background knowledge about this specific scene. Also, he must be able to recognize the dynamic actions of the avatars such as crying for help. We do not, however, need to please the human senses as is the case when producing virtual movies.

Geospatial information comes into play, because the surroundings of an actual city must be provided. The necessary 3D city model has been generated based on high resolution aerial and terrestrial images[5]. The city model has three roles: (1) most obviously it serves as a backdrop for the visualization of the scene, (2) it is also needed in sound modeling, because the reflection of sound depends on the surface material (land cover) and the location of obstacles (e.g., buildings), and (3) the city model also defines the areas where avatars can move around; for example, they can walk on roads and open spaces, but not through buildings and trees.

The goal of CROSSES is not to develop a geographic information system, but CROSSES has geospatial information at its core. It integrates 2D and 3D data and aspects of time. Besides data acquisition, each avatar needs real-time geometric routing for obstacle avoidance, and dynamic 3D visualization is a major component of the system. We have included this example in the paper because it illustrates the different requirements coming from the various applications. Whereas sound

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[5] The approach we have taken for automatic 3D city modeling focuses on building and trees and is described in Straub and Heipke (2001) and Gerke *et al.* (2001).

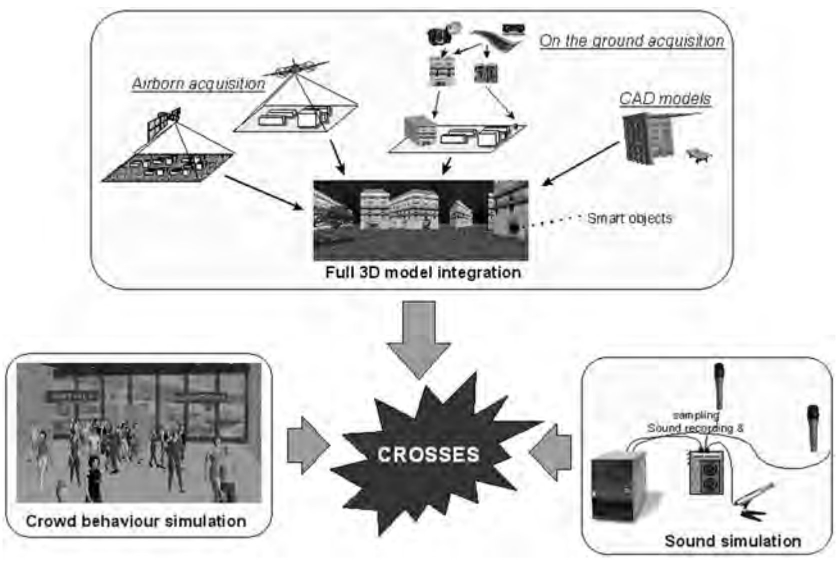

Figure 4. Components of the CROSSES system (color version at www.asprs.org).

Figure 5. Snapshot of a training scenario. A fire has just broken out, and various avatars are running around in the scene (color version at www.asprs.org).

modeling only needs a rather crude city model, and the avatar routing can effectively be done in 2D, the visualization requires a high degree of detail and a combination of information from aerial and terrestrial imagery, and all applications need consistent data. Realistic rendering of moving avatars requires furthermore a DTM whenever the city is somewhat hilly. A system like CROSSES can only be realized in a modular design, grouping the involved software components around a geospatial database with well defined interfaces (we use VRML in this project). As is often the case in such interdisciplinary projects, the geospatial information thus links the different components and provides the base for the whole project.

Quality Control and Update of Road Data from Imagery

In this section we describe work on automated quality control of roads given in the German ATKIS DLMBasis (see Busch and Willrich (2002) and Willrich (2002) for a more detailed description). In Germany we have approximately 1.1 million km of roads, and it is estimated that there are 10 to 15 percent changes per year. At the same time, roads are probably the most important topographic objects of the country. Therefore, it is of paramount interest to have a high quality road database which implies very short updating cycles. In central Europe such cycles can hardly be reached using optical imagery due to clouds. Nevertheless, a periodic quality control of the update information, acquired by other means, with the help of imagery is an important safeguard against the deterioration of the database.

In a common project between the Bundesamt für Kartographie und Geodäsie (BKG, Federal Agency for Cartography and Geodesy) and the University of Hannover (IPI, Institut für Photogrammetrie und GeoInformation, and TNT, Institut für Theoretische Nachrichtentechnik und Informationsverarbeitung) we derive a quality description for ATKIS DLMBasis road data. Our developments exploit the ATKIS scene description while extracting the roads from the panchromatic orthoimages and comparing the extraction results to the ATKIS information.

The system being currently developed is designed to combine fully automatic analysis with interactive post-processing by a human operator. The development is embedded in a broader concept of the knowledge-based system geoAIDA (Liedtke *et al.*, 2001), providing functionality from photogrammetry, geographic information science, and cartography for the acquisition and maintenance of geospatial information. The system consists of three major parts (see Figure 6):

- a GIS component which basically selects and exports the road data from a database, and provides for manual post-editing of the results;
- an image analysis component, which automatically checks the existing road data (verification) and checks the imagery for additional roads (change acquisition); and
- a process control component which derives the strategy for image analysis routines from the GIS data.

The most challenging task is the realization of the image analysis component. We use the approach developed at TU Munich by Wiedemann (2002). The algorithm is optimized for open, rural terrain and has been adapted for our specific task

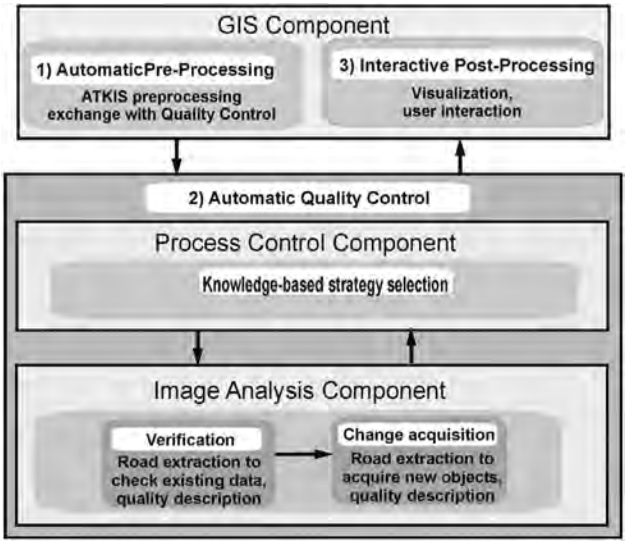

Figure 6. Components of the ATKIS quality and update system (adapted from Willrich (2002)).

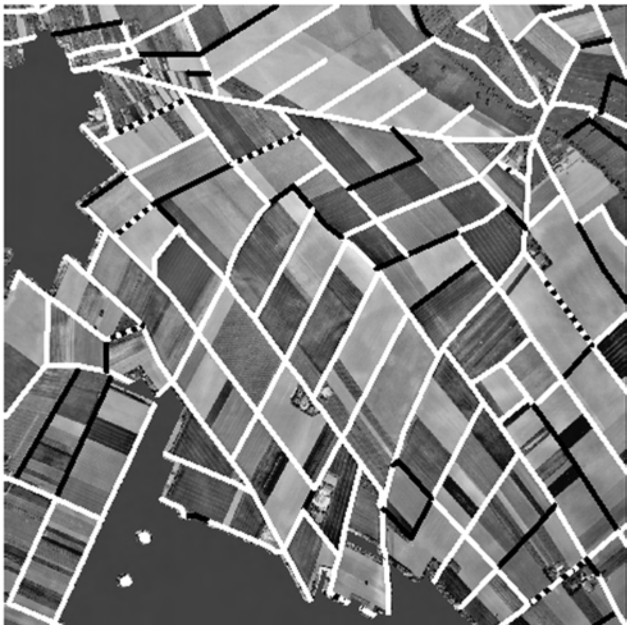

Figure 7. Results of road verification (white roads are *accepted*, dashed roads are *ambiguous*, black roads are *rejected*; from Willrich (2002)).

by incorporating prior GIS knowledge, for example, the road direction in the verification step. For quality control, we classify the road extraction results into three groups, namely, *accepted*, *ambiguous*, and *rejected*. In verification, *accepted* means that a road contained in the database could be extracted from the imagery, *rejected* refers to roads not having been found in the image, and *ambiguous* means that based on the derived results a decision cannot be taken. In change acquisition another class, *new roads*, is generated, however without a quality description at the present state of development. Currently, the classes *ambiguous*, *rejected*, and *new roads* are reported back to a human operator for further processing.

The system has been tested with 30 ortho-images covering an area of 10 by 12 km^2 near Frankfurt am Main. The ortho-images are available as standard products from the State Survey Authorities and have a ground resolution of 0.4 m. The investigated area contains approximately 5,000 roads in rural landscape. Seventy-nine percent were accepted by the system, 17 percent were rejected, and in 4 percent no decision could be taken. Because the images and the ATKIS data were from about the same time period, change acquisition did not yield any statistically relevant data. Figure 7 shows an example of the obtained results.

They demonstrate the usefulness of the described concept and the implemented prototype. In the near future we will investigate in more detail the reasons for rejection, improve the change acquisition sub-system, and look at the role of road crossings for verification and in particular for change acquisition.

The project is a good example of the integration of photogrammetry and geographic information science. Although the different components are not yet fully combined as in the ideal system described in the section on GIS and Imagery, the trend is more than evident.

The Radial-Topological Algorithm for Integrating 2D Geospatial Information and a DTM

This last example describes recent work in the domain of 2D/3D integration.[6] The developed method integrates existing piecewise linear 2D data into a TIN. The basic principle of the algorithm is illustrated by Figure 8.

The area of a triangle and its neighbors as well as its incident edges and points may be distinguished into distinct geometric locations. The basic primitive for this operation is the determinant computed by an oriented edge of the triangle and a point of the 2D data to be integrated into the TIN. The determinant will provide by its sign information whether the point lies to the left or right of the respective edge and, in addition, it will deliver the area of the triangle given by the edge and the point. If the area equals zero, the point must be collinear with the edge; however, it is not yet known whether it lies between the end points of the edge or somewhere else on the line formed by the end points of the edge.

Combining all three determinants computed from the test point and the three edges of a triangle provides information on whether the point lies on an edge or on a point of the triangle, or inside the triangle itself. If the location of the point is outside the triangle, the combination of determinants delivers an adjacent triangle which serves as input for the next determinant test.

Extending this approach leads to a procedure which sequentially integrates points and edges of the 2D data into a TIN, while navigating along the 2D data. The basic primitive for this operation again is the signed determinant. The respective determinants computed by the edges of the incident triangles and the end point of the next line segment to be integrated into the TIN will provide information about where the next point is located. On this basis, the 2D data can be integrated into the TIN. As the basic operation in this algorithm is a radial sweep combined with a topological walk along the 2D data and in the TIN, the algorithm is termed the *radial-topological algorithm*.

The above procedure solely inserts 2D data into an existing DTM-TIN. To derive a fully object-based model of the landscape, geometric features (points, lines, areas) have to be linked to their respective objects. Whereas point and line

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[6] The description given here leans heavily on the PhD thesis by Ulrich Lenk; see Lenk (2001) and Lenk and Heipke (2004).

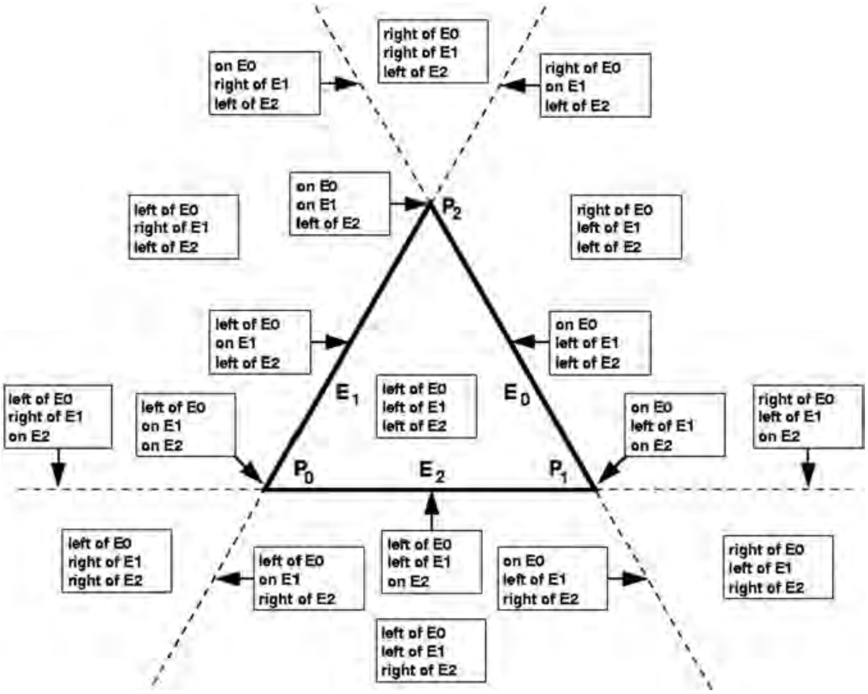

Figure 8. Division of the plane for the radial-topologic algorithm (see text for details; from Lenk and Heipke (2004)).

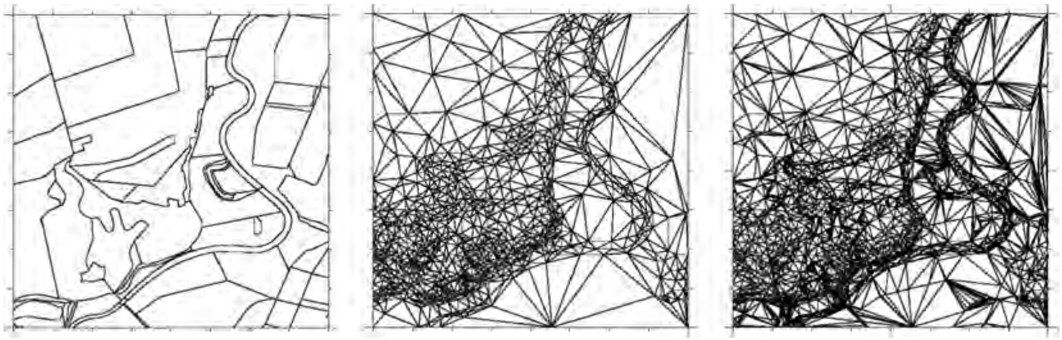

Figure 9. The example Leine: 2D geospatial information (left), DTM-TIN (center), integrated data model (right) (adapted from Lenk and Heipke (2004)).

features can be linked to the objects with moderate effort, the situation for area features becomes a little more complex (see Lenk and Heipke (2004) for details).

We illustrate the results of the algorithm with Figure 9, showing the Leine floodplain south of Hannover. The Leine runs to the south along the base of a small mountain and may be easily identified. The Eastern part of the area shows the floodplain with low relief energy. In the left of Figure 9 the 2D geospatial information is depicted, in the center one can see the DTM-TIN, and to the right the integrated model is shown.

This last example demonstrates that, while the algorithms for an integration of 2D geospatial information and a DTM are complex, this task can be successfully accomplished today. It is estimated that such algorithms will be implemented into commercial GIS in the near future.

Summary and Conclusions

In this paper we have discussed various requirements for modern geographic information systems. They shall be repeated here in a coherent form.

- The system should provide a topologic data structure, and it should be possible to model 3D geo-objects as objects following the object-oriented paradigm, which can change over time and scale with multiple representations per object.
- A modern geographic information system needs to be able to cope with imagery and contain modules for acquisition, update, and processing of 3D geo-objects from imagery, traditionally considered as part of a digital photogrammetric workstation.
- The system should provide an efficient and automated update and refinement work flow using images and other data sources including incremental update and versioning.

- The GIS should contain tools for data integration, and it should be an interoperable system based on international standards.

Currently, systems available on the market are rather far away from this ideal system, but research and development efforts are under way and will hopefully meet these and also other requirements not discussed in this paper, e.g., relating to database management systems, analysis, visualization, and dissemination of geospatial information. Only if these requirements are at least partly met, can we hope to successfully cope with the challenges involved in applications like setting up a European geospatial information infrastructure and location based services.

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