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Advancement of Mobile Geoservices: Potential and Experiences

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1. Introduction

Mobile information technology opens new perspectives and dimensions for the geosciences, by providing experts in governmental and non-governmental authorities, industry and science with ubiquitous access to geoscientific information. With this new instrument the digital acquisition, management, visualization, and analysis of geodata needed for the understanding of geoscientific processes and natural disasters can be supported directly in the field.

The number of applications is increasing where geoinformation systems (GIS) have to cooperate with distributed mobile applications and with suitable geodatabase management systems (*Balovnev, Bode, Breunig, Cremers, Müller, Pogodaev et al.*, 2004). The current paradigm shift from the development of monolithic GIS to flexible and mobile accessible geoservices can be recognized in many application fields. New geoservices will provide ubiquitous access to geodata needed in applications such as environmental monitoring and disaster management. Client applications communicating with geoservices have to efficiently acquire, visualize and manage application-specific 2D and 3D objects and complex spatiotemporal models (*Breunig, Cremers, Shumilov & Siebeck*, 2003).

In this contribution a geoscientific case study dealing with the analysis of land slides shows the potential behind mobile geoservices. Contributions to a distributed software system (*Breunig, Malaka, Reinhardt & Wiesel*, 2003) consisting of geoservices used by on-site clients for geodata acquisition, viewing, augmented reality, and geodata management are presented. The clients communicate over network with geodatabase services. Experiences are reported and finally, conclusions and a short outlook are given which address further research in the field of mobile geoservices.

2. Objectives of the project

The concrete problem we are referring to in this project is the analysis of land slides at an area near Balingen in south-west Germany (*Ruch*, 2002). Since several years there are active creeping movements of the terrain, which may endanger the traffic and people using a nearby road. The geodetic measurements show a gradual sinking of the soil and rocks. A forecast for a slowing down or speeding up of the movements cannot be given. However, mobile data acquisition of the ongoing movements and remote data access to a central station help to watch the situation. The movement measurements are done by extensome-

Figure 1: Clefts in the Balingen case study area with extensometer measurement units

ters located in some of the biggest clefts (see figure 1). If conspicuous extensions of a monitored cleft are registered, an alarm is triggered and the local road is closed immediately. In this case a geologist then has to go to the area and decide if this was a false alarm or if the next landslide can be expected shortly. The main objective of the project is to show the potential of mobile geoservices prototypically for geoscientific applications like the Balingen land slide example.

The available primary data of the Balingen examination area are fixed points with direction vectors, measurement plots of the extensometers, a digital elevation model, contour lines, path network, structural edges and slopes in scale 1:250. From these primary data the following interpreted data are constructed: stratigraphic boundaries and 3D strata bodies.

Typical requirements of the Balingen case study to geoservices are:

- Storage of 2.5D geodata (digital elevation model), measurements data, and 3D models.
- Retrieval of stored geodata and computed deduced 2D profile sections.
- Online geodata acquisition and analysis of the terrain.
- Geodata editing of rocks and clefts in the terrain.
- Viewing of primary and interpreted data in the terrain. Overlapping of the 3D model with the physical reality by AR methods.

The Balingen case study is a well-suited example to demonstrate the use of modern geoservices supporting environmental monitoring and prediction in the geosciences.

3. Methods & results

3.1 Mobile acquisition of geodata

For the mobile geodata acquisition in the given project environment of the Balingen case study, four main objectives have been investigated:

(a) Refinement of concepts for mobile acquisition of geodata.
(b) Development of a prototype system.
(c) Definition of a detailed concept for the quality assurance.
(d) Proof of concepts – Application of the system to the »Balingen test area«.

3.1.1 Refinement of concepts for mobile data acquisition

This point included in particular the following important research issues:

- The development of refined workflows for mobile acquisition of geodata, which make fully use of ubiquitous access to various sources of information. This includes the selection of the servers and the download of the data usable for the current application, the feature acquisition, update etc. The specific requirements of these workflows during mobile online data acquisition have been analysed, evaluated and finally the application has been adjusted accordingly.

- Multi-sensor treatment: In the user scenario in the Balingen test area, different kinds of sensors like GPS receivers, total stations, extensometers and even laser scanning devices have to be considered. In future OGC standards like SensorWeb or SensorML will allow for an interoperable access to these sensors. Until the sensors manufacturers support these protocols alternative options have to be considered. The use of common standardised protocols like e.g. NMEA for GPS receivers allows for an access to many sensors of that specific kind independent of a certain vendor. This enables the application to access and control a maximum number of sensors.

- Technical issues like the connectivity via wireless techniques have been investigated. In rural and especially forested areas cellular radio and WLAN have to be combined in order to fully cover an area of interest and to transfer the data to the server. Some of the experiences made are summarised in section

3.1.2 Development of a prototype system

A prototype for mobile data acquisition of geodata has been developed. The most important guidelines for this development have been:

- Development of an open architecture based on standards, which means that no propriety vendor dependent modules and interfaces have been included. Proprietary interfaces constrict in particular the connection to the disparate data services and the applied sensors. Hence for the access of the heterogeneous distributed servers standards like the OGC web map and feature services (WMS and WFS) and the geographic markup language (GML) have been employed. As mentioned in the previous section the control of the sensors and the transfer of the measurement results should also be based on standardised interfaces (if possible).

- A generic approach of data acquisition has been developed which allows using the system in various applications. Therefore the client application has to be able to adjust itself to the requirements imposed by the data model. In particular, the measuring process and the templates for input of further attributes must be flexible and adaptable. The standardised service interfaces mentioned above are self-contained and self-describing. The client application is using these features for the purposes of data access and acquisition. This means the client application downloads capabilities (supported operations and existing feature classes) and schema information of the server at runtime. Such XML-schema contains all necessary details about the modeled feature types, their geometry and associated attributes as well as the interrelations between features of one or different types. With the information contained in the XML-schema, it is possible for the client application to adjust the acquisition process with regard to the required attributes, geometry types and relationships of a particular feature type and to guide the user through the whole data collection procedure. The templates for the input of attribute values are generated automatically at runtime and the process of measuring geometry elements is adjusted to the requirements of the feature type currently being measured. This will assure that the collection of the data is conforming to the schema provided by the particular server. (*Mäs, S., Reinhardt, W. & Wang, F.* 2005a)

- The architecture of the client software allows for an easy extension and adaptation to the requirements of a particular application. Section 3.2 (Graphical geodata editor) includes further explanations regarding this.

3.1.3 Quality assurance concept

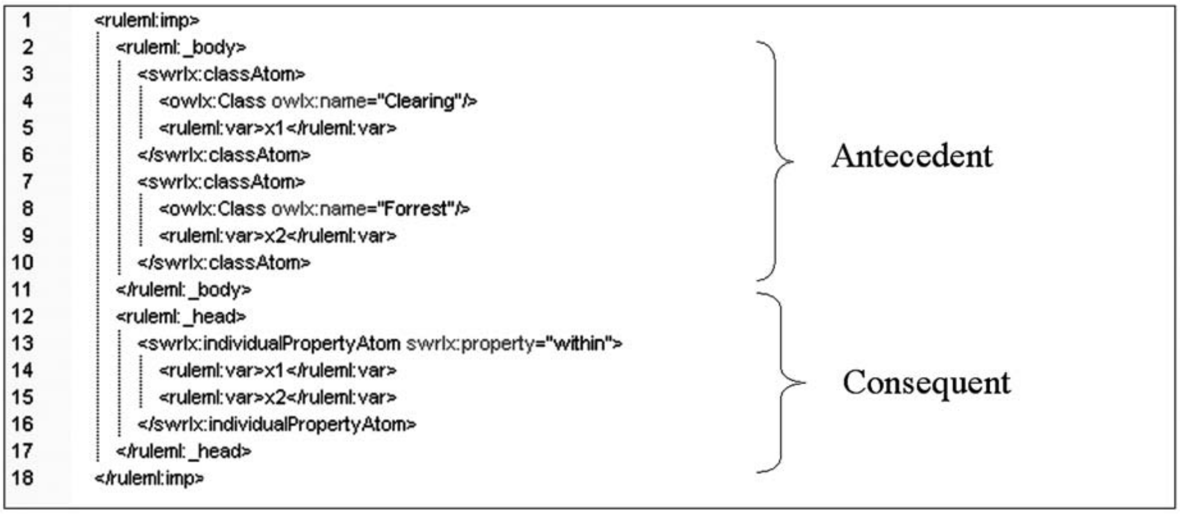
The mobile interoperable access to heterogeneous geodatabases and their update from the field has far reaching consequences for the data acquisition process. As mentioned before, this approach provides the possibility to check the newly acquired data in terms of quality and reliability directly in the field, which makes quality management investigations necessary. In our work specific focus was given on finding a way to define integrity constraints and transfer them to the client in a standardized way, as additional information to the XML schema available through the WFS. These constraints allow for related automatic checks during data collection in the field. Therefore it has been investigated how spatial and other constraints can be formalised in SWRL (Semantic Web Rule Language, W3C 2004b), which is a combination of OWL (Web Ontology Language, W3C 2004a) and RuleML (Rule Markup Language).

The defined constraints can be applied, for example:

- on spatial relations between objects of the same or of different classes,
- on a single or numerous attribute values,
- on a defined relation between two attribute values of one object,
- or on a combination of spatial relations and attribute values of different objects.

The rules are not restricted to relate only two object classes or attributes. Even complex spatial and topological relations between numerous spatial objects, together with their attribute values, can be described.

A simple example of a quality constraint for geospatial data is given in figure 2. In natural language the meaning of this rule is: »a clearing is always within a forest«. The two atoms in the antecedent define variables for each one of the object classes. In the consequent these variables are used to set the object classes in



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      <ruleml:var>x2</ruleml:var>
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  </ruleml:_head>
</ruleml:imp>
```

Figure 2: Example quality constraint encoded in SWRL.

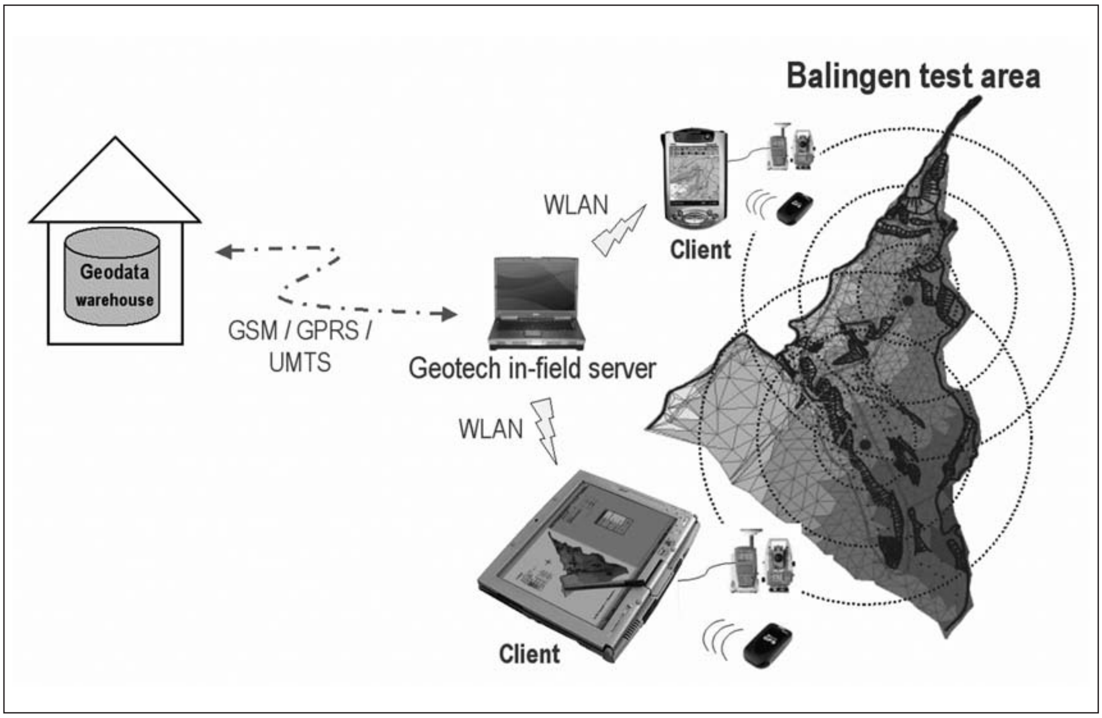

Figure 3: System configuration for the Balingen test area

relation. Therefore the »Within« relation is employed. The denotation and the definition of such spatial relations refer to the spatial operators defined in OGC Filter Encoding Implementation Specification (OGC 2001). More details regarding the constraint formalisation in SWRL and the quality assurance concept can be found in *Mäs et al.* (2005b).

3.1.4 Proof of concepts – application of the system to the »Balingen test area«

As mentioned before the proposed mobile client system should support the decision-making process of the geologist in case of an alarm. The concepts and prototype implementations have been proven in the Balingen test area. Therefore a data model has been defined in cooperation with the users and a WFS server has been set up. This data model and the alarm scenario are described in more detail in *Kandawasvika et al.* (2004). Figure 3 shows the system configuration for the field tests.

Central component of the configuration has been the »Geotech in-field server«, which is normally installed in a car at a point where a connection to the central geodata warehouse via GSM / GPRS / UMTS is possible. This connection might not be necessary in every case. Sometimes it is better to have the database and the service directly running on the in-field server, depending on the data volume and the available bandwidth / transfer rate. With the in-field server and a locally installed WLAN it is possible to support several mobile users at the same time. Mobile units are preferably tablet PCs, because of their capacity and performance, but the client application should also support other devices. For the data collection GPS and total station have been used as measurement devices.

In practical tests we found out that the whole area of around 200* 150 m^2 can be covered by using only 2 WLAN access points (high-end APs and antennas). Please notice that our examination area is a very steep (50m height difference), undulated terrain, which is covered by tall trees. The user is able to move in the whole area e.g. with a tablet PC always being connected to the geodata warehouse (via the in-field-server).

The performed field test verified the practical advantage of the developed concepts for the geologist field tasks. The support to the geologists included:

- Online request and visualisation of available existing data
- Positioning in the map
- Possibilities to analyse data and do inspection measurements
- Validation of the alarm
- Acquisition of new features like e.g. ditches or gaps
- Quality assurance of these data

The quality assurance process not only does it help to acquire data conform to the server data model, but it also supports the decision-making process and helps to identify dangerous situations that are not always obvious to see. For example a constraint prohibiting a publicly accessible way to be in a certain distance to a ditch would lead to an automatic warning to the geologist while measuring such a newly formed ditch. It is then up to his decision if and how to react: he might close the way for public access or at least mark the danger with some warning signs. Anyway, for traceability he has to document his decision in the system.

3.2 Graphical geodata editor

A central component of the mobile acquisition system is the graphical editor for geodata (see figure 4). It is implemented as a lightweight Java application running on the mobile device, e.g. a ruggedized Tablet PC. The editor constitutes the user interface of the mobile data acquisition system and provides the core functionality for acquiring and editing geodata in the field. The central element of the editor GUI is a map which displays the geodata received from the server. The usual tools for navigating the map (pan, zoom), getting information about features and editing their attribute data and geometries are being implemented.

A straightforward possibility for the visualization of the GML feature collections received by

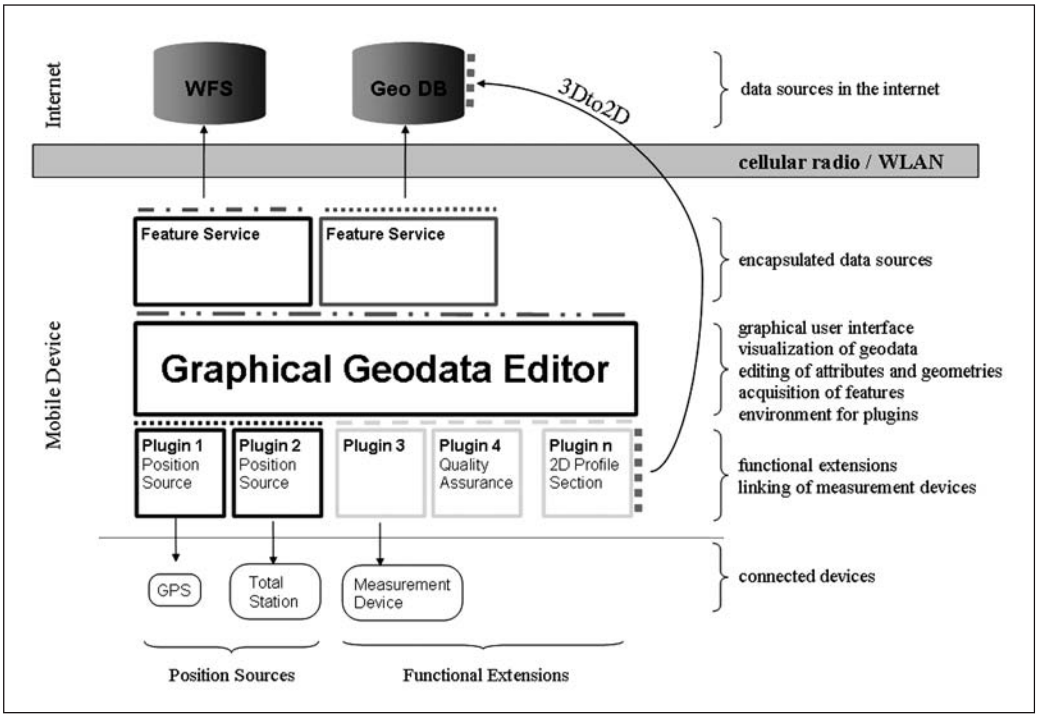

Figure 4: Architecture of the mobile acquisition system

WFS is the transformation to SVG using XSL transformations (XSLT). In this context, we have investigated whether and how SVG can be used to visualize and store geodata within a Java SVG implementation. As implementation of SVG, we have chosen the open source Apache Batik framework. This framework supports SVG rendering and access to the SVG DOM from Java applications. We investigated how to manage the geodata with all its non-geometric attributes on the client (in memory). It is not desirable to store the data redundantly, e.g. as SVG DOM and as objects of a GIS library in parallel. So, we need to hold all spatial as well as non-spatial attributes of the GML features in the SVG representation. While the GML geometries can be transformed to SVG geometries, the non-spatial attributes of the features can be stored in »svg:metadata« elements. This is a standardized mechanism to embed arbitrary metadata within SVG documents. It is also possible to insert elements of other namespaces into a SVG document. The Java SVG binding provides possibilities to address particular nodes in the SVG DOM directly. This allows manipulating SVG subtrees representing single geographic features. We realized a simple way to keep all the geodata in one SVG DOM including a change history (during one editing session) for each feature attribute.

When geodata is represented as SVG it is necessary to transform from GML to SVG and also back from SVG to GML in order to write edited data back to the server. In order to develop a generic application we had to investigate the general possibilities and restrictions for bidirectional XSL transformations between GML and SVG. We used Styled Layer Descriptor (SLD) documents for the definition of the visual attributes of the different feature types. In *Merdes, Häußler & Zipf* (2005) it is shown, that it is possible to build a generic application without the necessity for application developers to write any application or domain specific code by using the self-describing mechanisms of the WFS services and SLD as styling definition.

To integrate additional functionality for more specific application scenarios we have developed an architecture and runtime engine for plugins. These way parts of the additional functionality can be integrated into the core editor keeping the actual editor component thin. Thus the system can be adapted to the application scenario and also fosters the desired reusability of the software application. The SVG representation of the geodata inside the core editor is transparent to the plugins.

One group of plugins is »position sources«. As position sources we denote plugins that provide geo-positions with semantics well known to the user. Examples of position sources are GPS and total station. A position source plugin encapsulates e.g. a single GPS device and provides its measurements to the editor environment, together with additional information like timestamp, precision etc.. With such a plugin the current position can be displayed on the map. Several position sources can be connected simultaneously. The plugin infrastructure makes it possible for all plugins to connect to all registered position sources at any time making the editor a very flexible platform for additional and more advanced functionality. Other devices which do not function as position sources can connect e.g. other measuring devices which deliver measurements for non-geometric attributes of new or existing features (temperature, soil parameters, precipitation measurements, etc.). Triggering of a single measurement or a series of measurements in certain spatial or temporal intervals and insertion of the respective located measuring point(s) into the database are possible that way.

A third group of plugins are those that do not link hardware devices to the editor, but provide other kinds of functionality. Examples of such plugins include:

- A feature acquisition plugin which generates and adds new features using the position sources as input for the new geometries.
- A plugin for quality assurance that controls the correctness of the edited features performing topological tests.

- A 2D Profile Section plugin: The user defines a planar profile section in the map of the editor and gets a 2D profile generated by the 3Dto2D service described in section 4.4.

The described infrastructure provides a flexible and extensible solution for a mobile open standards-based geodata editor.

For the described Balingen case study there are several ways in supporting the geologist with such a system. As there is online access to the geodata, the geologist does not have to go to the office (which in our case is hundreds of kilometres away) to consult the latest data. In the case of a false alarm, this makes it possible to bring the endangered road into service again very quickly. Furthermore, observations of the geologist can be added to the geodatabase server directly in the field, therefore being immediately accessible by other specialists. The quality control plugin could widely make post processing of the data superfluous, which is again important due to the big distance between the monitored area and the office. Decision making is assisted by the availability of calculation-intensive services like the mentioned 3Dto2D service, which is important for (infield) interpretation of the acquired data.

3.3 Augmented reality client

A mobile AR prototype system (see figures 5 & 6) has been designed and developed (*Wiesel, Staub, Brand & Coelho*, 2004), to support geoscientists in the field. The system is based on an IEEE1394 camera and a monoscopic Head Mount Display (HMD), hardware for navigation, an inertial measurement unit (IMU) and the necessary computing equipment mounted on a backpack.

The system has been designed to allow a human to move around in the test area and analyse the geological structures and landslides by
- Inspecting the scene.
- Overlaying the terrain with time stamped 3D geodatabase content (e.g. profiles or displacement vectors, geological data).
- Gathering new geodata (e.g. new clefts or rifts).
- Entering and editing geodata in real time

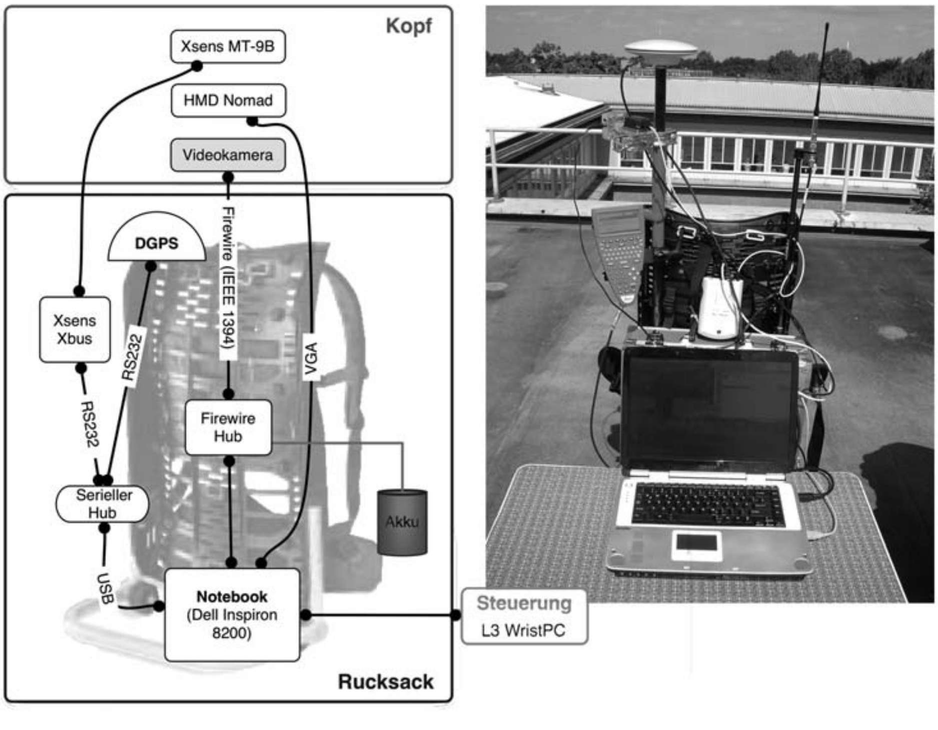

Figure 5: Proposal for an Augmented Reality System Architecture and Hardware Mockup

Figure 6: Testing the proposed ARS outdoors

into the geodatabase.
- Entering attribute data into the database.
- Writing reports about current situations in the field.

Navigation and orientation of the sensor system (based either on a camera or a head mounted display) is crucial for the usability of such mobile AR clients. We have combined a GPS-receiver and a low cost IMU to achieve a positioning precision in the cm range.

By using Real Time Kinematic (RTK) GPS positioning we can achieve a positioning precision down to ±1 cm. Yet, in a typical geoscientific application, we have to deal with GPS dropouts while moving around in the field. To overcome this problem we are using an IMU mounted on top of the system, which can provide velocity, position and attitude of the HMD and camera for a short time period. Ongoing studies (*Staub, Coelho & Leebmann*, 2004) calibrate and filter sensor readings to close the gaps of satellite signal outages.

Furthermore, we use a so called wrist-worn keyboard to interact with the system. Many important features are implemented so far and can be triggered by predefined keyboard shortcuts. For example, it is possible to change the transparency, line width of the virtual objects or the lighting conditions of the virtual scene, as well as loading or removing objects. It is also possible to zoom in the scene, pan and rotate the virtual objects. The feedback signal sent by the ARS after receiving such a command is either visual or acoustic. This depends on the action performed by the user.

The human computer interface had to be designed straightforward without occluding the area of interest in the »real world«. Therefore, a transparent interface with minimal contents and alternative controls on demand is proposed. It consists of permanent output of the user's position (Gauß-Krüger coordinates and ellipsoidal height) and orientation, which is shown in the upper-most position of the display. An overview window is placed at the lower right corner of the display, which can be removed if it is occluding some important objects. These three components combine all the necessary positioning and orientation information to give the user knowledge about his (or her) location in the field. In the centre of the field of view a crosshair is displayed. This is used for capturing additional information from virtual and real objects. This is a useful feature of the ARS, because it offers the possibility to receive information about the objects in real-time. Non-visible information is gathered from the artificial objects.

To achieve a realistic impression of the superimposed scene, it is important to provide a smooth transition of virtual and real objects. Depth information is needed to fit virtual objects into the environment, which may occlude parts of the virtual scene. In urban environments, the developed ARS uses additional building models to retrieve depth information and to compute occlusion (*Coelho*, 2004). In the context described in this article, the user has to operate in a forest. No information on the location and size of trees, which are the main source of occluding objects, is available. To operate in such an environment, a head-mounted stereo camera system is used to obtain necessary depth information on the fly with a dense two-frame stereo algorithm.

In the Balingen test area, newly discovered clefts or rifts have to be surveyed by a geo-scientist. Therefore, (*Leebmann*, 2005) proposes a methodology to gather such information from a distance. It is necessary to survey the object of interest from a minimum of two different points of view. This way it is possible to calculate the Gauß-Krüger coordinates. Figure 7 shows the approach tested by surveying an edge and the augmented view on it after calculating its position in the field.

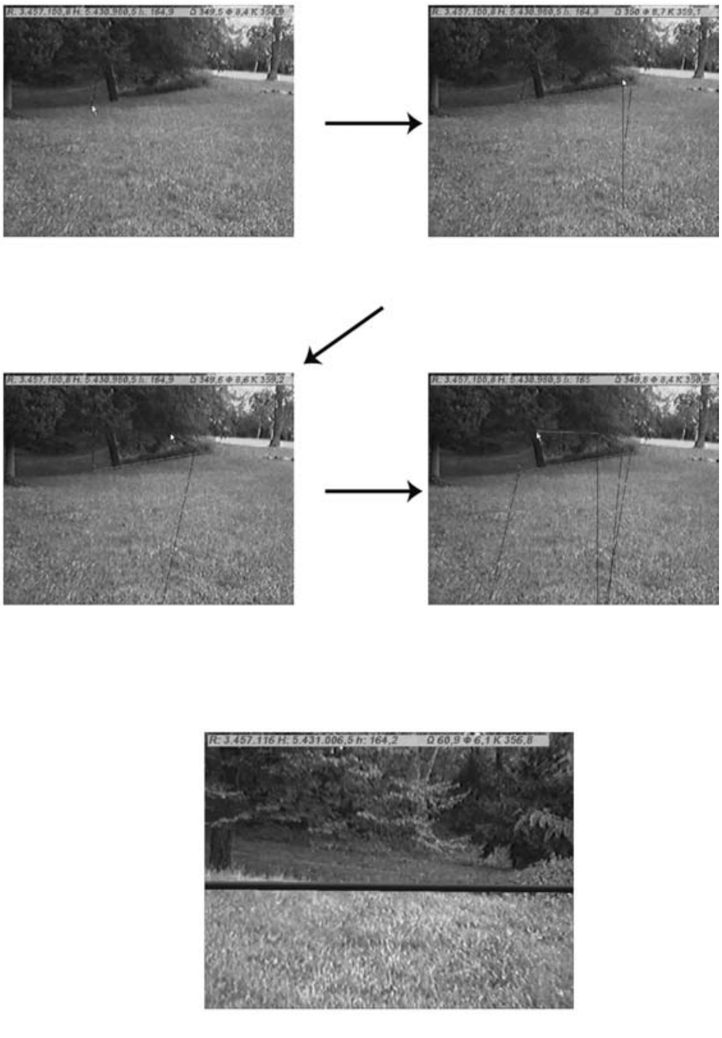

Figure 7: Survey an edge in terrain

3.4 3D geodatabase services

In order to provide geoservices accessible by arbitrary mobile clients, a 3D geodatabase system should provide an open service architecture giving access to the whole functionality of the underlying geodatabase, while ensuring the communication with the mobile clients based on interoperable open protocols.

In the prototype of our 3D geodatabase system the service framework is provided by a rich set of single services implemented as remote method calls in Java. The service framework supports the combination of the single services to so called service chains – which are then capable of providing complex processing capabilities inside the database system. The data transfer between services and clients is primarily based on the extensible markup language with an associated XML schema. The output services currently cover a specialised XML format, VRML and X3D, and are extensible by the user through XSL transformation to arbitrary XML and text based formats.

To support applications like the Balingen land slide scenario, the geodatabase services must provide access to and update capabilities of entire 3D-models and related geometric and thematic data from mobile devices in the field. The following sections give two examples of our 3D geodatabase system which are meant to address these capabilities. The first example describes the support of constraint mobile devices (PDAs), which are not yet capable of working with complex 3D models, through a special application service. The second example explains our ongoing research with supporting update capabilities on mobile devices through the usage of mobile databases integrated with the server geodatabase system.

3.4.1 Supporting constrained mobile devices

A comprehensive subsurface model may consist of hundreds of geological bodies, each represented by complex objects, e.g. triangulated surfaces or volumes, composed of up to more than a hundred thousand elements (e.g. triangles or tetrahedrons). Considering constraint clients, e.g. PDAs combined with a GPS, both the transmission and the graphical representation of such a complex model are not yet realistic, because of insufficient available bandwidth and performance of the graphical display. On the other hand, the geoscientist in the field often needs only a selected part of the information, specified by e.g. a 3D region, a stratigraphic interval, a set of thematic attributes or some other geometric and thematic criteria. Even such reduced information may be too large for use in the field, motivating the use of techniques of data reduction and progressive transmission (*Shumilov, Thomsen, Cremers & Koos*, 2002).

Therefore – due to today's hardware restrictions on PDAs - graphical representation of a 3D model could be reduced to a sequence of 2D sections and projections. By sliding through successive sections, even a 2D display can provide insight into the form and structure of a complex 3D body. However, this means that services have to be provided that compute 2D profile sections for arbitrary planes of a 3D subsurface model. Such a service allows the field geologist to compare the actual observed situation with information provided by the subsurface model, and to take decisions on sampling accordingly.

We are exemplary presenting such a service, the so called 3Dto2D-Service. It provides the derivation of 2D geological profiles from a 3D subsurface model for a specified arbitrary plane in the 3D space. Additionally, further objects spatially located in a specified distance to the plane, which are of interest for interpretation, can be projected onto the computed 2D profile. The service is composed of the following single services provided by our service framework (see figure 8):

- RetrieveService – supports queries on complex geoscientific 3D models.
- PlaneCut – cuts a planar profile through the 3D model for a spatially specified arbitrary 3D plane.

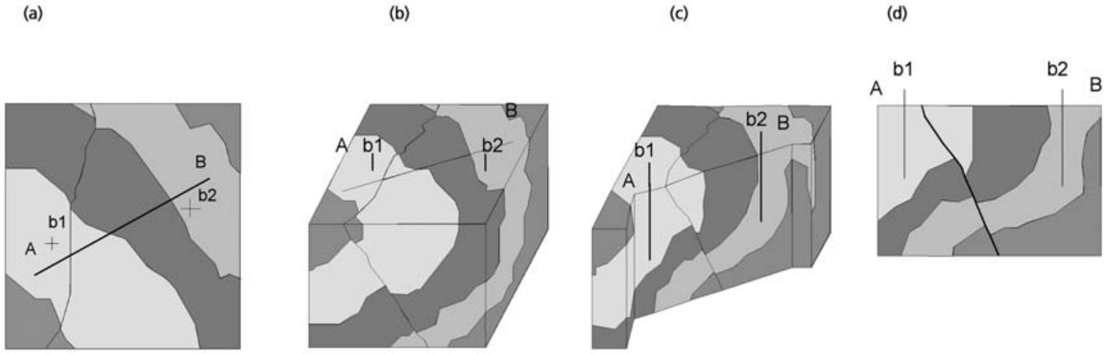

Figure 8: 3Dto2D service

- PlaneProjection – projects interesting 3D objects onto the plane profile, which are spatially located in a specified certain distance of interest to the 3D plane.
- AffineTransform – transforms the resulting 3D objects into a 2D xy plane.

Figure 8 shows the principle steps. The user may specify a planar profile section between endpoints A and B, with further data such as spatially neighboured boreholes b1 and b2. Figure 8 (a) shows the location in map plane view. The block view of the 3D model is given in figure 8 (b) and figure 8 (c) shows the view of profile section with part of model removed. Finally figure 8 (d) shows the resulting 2D profile section with the projected borehole profiles as additional information.

Each of the single services of the 3Dto2D-Service implies geometric operations requiring a considerable amount of time (*Breunig, Bär & Thomsen*, 2004). Therefore, in order to reduce the length of transactions, the single services are operating each in transactional mode. Single failures of one service can be compensated by restarting this single service, and do not require starting the whole service chain from the beginning.

3.4.2 Supporting update operations with detached mobile databases

A 3D geodatabase system for geological applications should enable the geologists in the field, as well as in the laboratory, to refer to a shared common 3D model during the process of data caption, processing, interpretation and assessment. The cycle of steps involved in updating a geological model can be rather long and the result may never be free of subjective appreciation. Therefore it is advisable to use strategies of version management to control the evolution of the 3D model rather than supporting direct editing by transaction management.

In the following we will give an overview of how we address update capabilities in the field using mobile databases (*Bär & Breunig*, 2005). The approach is based on a version management extension of our 3D geodatabase server. The mobile database is regarded as a special client to this version management system and therefore updates on local 3D objects during offline mode are integrated back to the 3D geodatabase system as new revisions of the previously replicated 3D object. This approach makes it possible to review changes in 3D objects or to complete 3D models before they are merged to the original 3D model of the database system.

Therefore our 3D geodatabase system has been extended with version management capabilities. The generic version management extension is motivated by the object-oriented version model of *Schönhoff* (2002) and provides the management of history graphs of versions and a hierarchy of workspaces as version repositories. For an overview of version models we refer to *Katz* (1990).

Figure 9 gives an overview of the general structure of the version management system as

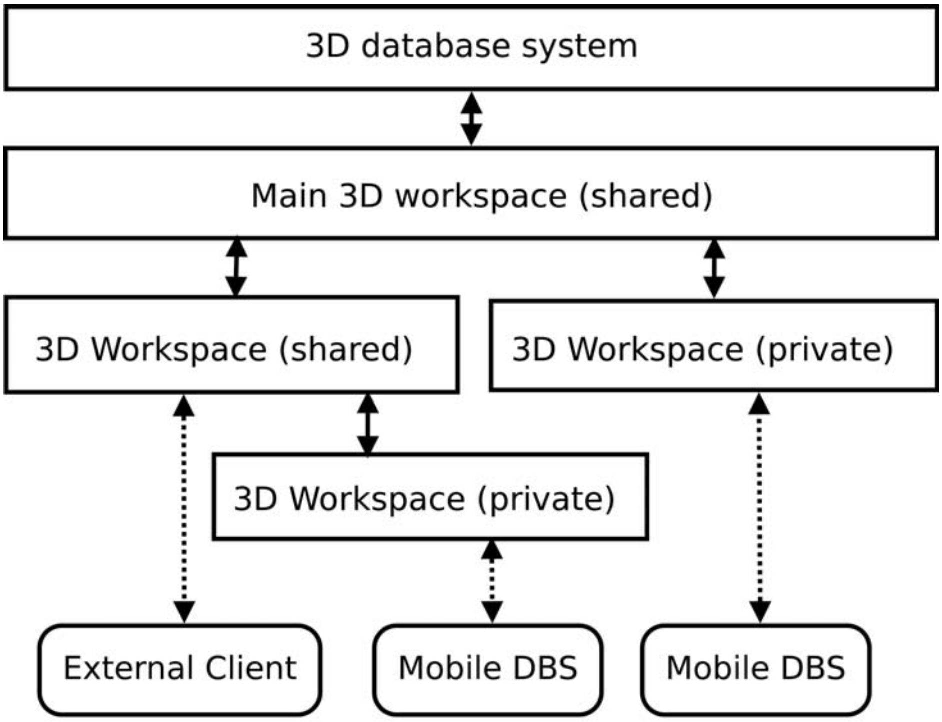

Figure 9: Structure of the version management system

seen by the user. The existing 3D database system is called the release database in which the releasable database objects reside. To modify a database object from the release database it has to be put under version control first. This operation creates a new design object for the database object and the initial version in the main workspace. Starting from this initial version, new modifications result in a new version of the design object. Inside a workspace there exist only revisions of versions (linear history). Modifications to versions which are meant to provide a rather alternative representation of an object are called alternative versions. Such alternative versions have to be created in a new child workspace with an own revision history. Propagating a later revision of an alternative version back to the parent workspace is called merging. To execute a merge, no conflicts with the latest revision in the parent workspace are allowed. Otherwise a conflict resolution must be done beforehand by the user. This way mature versions can be propagated upwards the workspace hierarchy and finally replace the original database object in the release database.

Besides the concepts of design objects and their versions, the concept of configurations has to be supported in the version management system. Configurations allow grouping specific versions of several design objects. With configurations the notion of 3D models from geology as a consistent set of several design objects can be realized. Therefore they must be extensible to allow forcing constraints on the added versions such as »no geometric intersection between the objects represented by the added versions is allowed«. Furthermore, configurations provide a way for batch propagation of a consolidated set of versions between the workspaces.

The version management presented so far does not force a specific representation of versions in the system. As the complex 3D objects used in geo applications can internally consist of up to several hundred thousands of simplexes, the storage of a complete object for each version is impracticable. Therefore, we represent a version as the set of changes to its revision or alternative predecessor in the version history (delta storage). Beside the reduction of used storage, this approach enables efficient algorithms for conflict detection and also for providing change histories. Having used simplicial complexes as the underlying data model of our 3D objects, the changes are represented inside the version management system as additions/deletions of single simplexes, complete components and the associated thematic changes. Conversion operations between the version representation and the database object representation ensure that all the operations from the geodatabase system can also be applied to the versions of 3D objects. This makes it possible for example to create profiles sections with the described 3Dto2D-Service from different versions of a 3D object and therefore to compare differences also on constraint devices in the 2D space.

The version management extension is integrated with the service framework of the geodatabase system. The communication between mobile databases and the version management is based on the XML representation of 3D objects or change sets between versions. Although the version management system was designed with the support of detached mobile databases (offline usage mode) in mind, the integration with the service framework also enables every mobile or static client to use the version management capabilities provided.

3.4.3 The 4D-Extension: Managing spatial objects varying with time

Landslides obviously involve changes of location and form of spatially extended objects depending on time. The modelling of displacements and deformations can be done by numerical models, or by a scientist designing a sufficient number of discrete states of the model at different time instants, based of observations and measurements. The task of the geodatabase is to manage the resulting time-dependent spatial objects (4D-objects), and provide services that allow to retrieve the state of a spatial object at any given time of its lifespan by appropriate searching and interpolation methods. The 4D-extension of the geodatabase is based on earlier experiences with the timescene tree (*Polthier & Rumpf*, 1995), with the GeoToolKit (*Balovnev et al*, 2004), and on concepts presented by *Worboys* (1995). *Rolfs* (2005) presents a detailed discussion of the spatiotemporal extension and its implementation as well as more extensive references.

A time-dependent spatial object is considered as a function defined on a time interval, with values in a set of spatial 3D-objects. This implies that in addition to the spatial model discussed in previous chapters, a model and a discretisation of time is required. It consists of time instants t and time intervals (t_i, t_{i+1}) that are concatenated to form time sequences. A number of temporal operations support set operations and predicates, especially to determine intersections. Searching is supported by a temporal index based on Bentley's segment tree, cf. (*de Berg et al.*, 2000). The temporal behaviour of objects is defined in an interface that is inherited by all temporal and spatio-temporal classes.

The central questions concern the discretisation of time and the necessary interpolation between discrete states of the object, changes of topology, i.e. of meshing and of connectivity. As the static 3D-objects of a geological model may already comprise meshes of considerable size (up to several 100000 elements), a simple repetition of slightly changed copies at each time step may result in intolerably big and redundant 4D-objects. Therefore, attempts are made to reduce redundancy in parts of 4D-objects that are either static or show only very small changes over time or changes that dependent linearly on time, by allowing for different density of discretisation in different parts.

Whereas the geometry (location, extent and form) of a 4D-object may vary continuously or by steps, its topology (meshing, connectivity) can only change at discrete steps. Moreover, it seems reasonable to assume continuous deformations and displacements taking place more

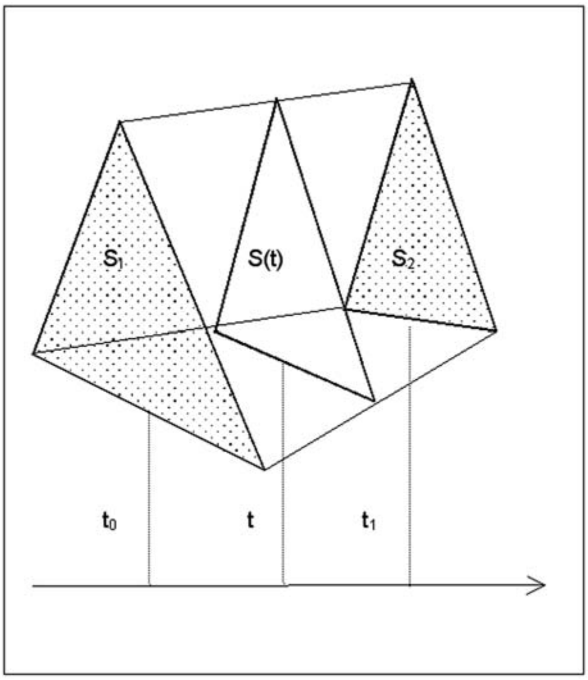

Figure 10: A spatiotemporal (ST-) element

frequently than disruptions or re-meshing because of extreme deformations or changes of size. The time-dependent geometry therefore assumes that a number of contiguous discretisation intervals where continuous displacements and deformations occur without change of topology, can be grouped together to larger time intervals at the boundaries of which meshing and connectivity change.

A 4D-object is composed of spatiotemporal (ST-) elements of two kinds: one is defined as a pair $(t, s^d(t))$, with a time instant *t* and a d-simplex $s^d(t)$, the other one is defined as a tuple $(t_i, t_{i+1}, s^d(t_i), s^d(t_{i+1}), f)$ – it consists of an open time interval $]t_i, t_{i+1}[$, a pair of spatial d-simplexes $s^d(t)$ defined at the interval boundaries, and an interpolation function *f* that, for any t in the open interval $]t_i, t_{i+1}[$, yields a snapshot $f(t)=(t,s^d(t))$, The present geodatabase supports linear interpolation of vertex co-ordinates, but the approach can be generalised to more elaborate interpolation methods. Considered as a 4D-geometry object, such an ST-element resembles a deformed prism (figure 10).

The ST-elements are grouped into a number of spatiotemporal (ST-) components, each with a common discretisation of time and a constant and connected mesh. Between spatially neighbouring ST-components, time discretisation may vary, and at the contact of subsequent ST-components in time, meshing and connectivity may change (figure 11).
Different discretisation in space or time may cause inconsistencies at the contact of ST-components. These might be avoided by carefully designing the 3D-objects, or by the user imposing appropriate constraints.

In a simple case, an ST-object may consist of a single ST-component, with a common time discretisation, and no discontinuities.

Besides methods for the loading and checking of ST-objects, for intersection with 4D search boxes, numerical functions etc., there are two main operations supported by an ST-object O^d to be mentioned:

1. The calculation, for any given time t within its interval of definition, of its *3D*-snapshot $S^d(t)$, yielding a ST-object, which is a d-simplicial complex in $\mathbb{R}^3$ with an additional time stamp, and can be subject to any spatial operation defined in the 3D-geodatabase.
2. The intersection with a 4D query box, resulting in a new ST-object defined by the intersection with the query box.

In principle, a combined spatiotemporal index can be defined by extending the well known R-tree to four dimensions. In the present model, however, separate indexes for time – a segment tree, and an R-tree for space are used, thus keeping in line with the static 3D- model (*Rolfs*, 2005).

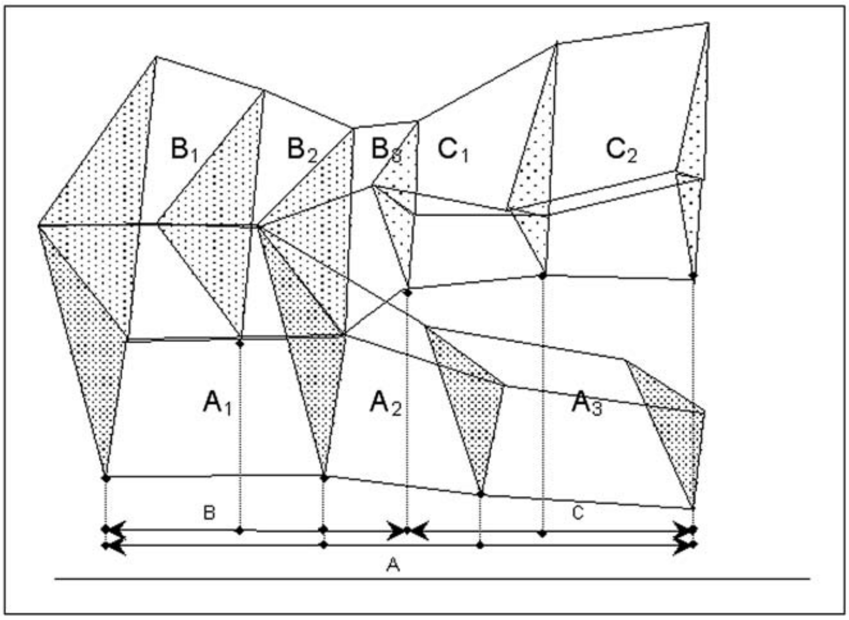

Figure 11: A spatiotemporal (ST-) object composed of 3 ST-components with different time discretisation

4. Conclusions

This contribution reported about typical geoscientific requirements to new geoservices. In a case study dealing with land slides at Balingen, south-west Germany, it has been shown that the mobile acquisition, visualization and management of spatial data can simplify geoscientific work by digitally supporting geoscientists directly in the field. Contributions of the project partners to a prototype of a distributed software system of geoclients and services usable by mobile geoscientific applications were discussed. A mobile graphical editor for geodata acquisition, a mobile AR client and geodatabase services were presented in detail. We are optimistic that in the future, the merging of the 3D database content with the live scene in real time executed by AR methods will help the geoscientific expert in the field efficiently to examine geological subsurface structures and to compare them with visible fault lines at the surface. The 3Dto2D geodatabase service, for example, meets the introduced geoscientific requirements by remotely computing 2D profile sections from a 3D subsurface model and by visualizing the database query results on the mobile client. For the future we see research demands in integrating single geoservices into geodata infrastructures and in developing new mobile data acquisition and visualization tools coupled by efficient geodatabase services.

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