On Creating a Spatial Integration Schema for Global, Context-aware Applications[1]

Steffen Volz, Daniela Nicklas[2], Matthias Grossmann[3], Matthias Wieland[4]

[2]Carl von Ossietzky Universität Oldenburg, Department of Computing Science, Escherweg 2, 26121 Oldenburg, Germany

[3]Universität Stuttgart, Department of Applications of Parallel and Distributed Systems, Universitätsstr. 38, 70569 Stuttgart, Germany

[4]Universität Stuttgart, Institute of Architecture of Application Systems, Universitätsstr. 38, 70569 Stuttgart, Germany

steffenvolz@gmx.de, daniela.nicklas@uni-oldenburg.de, grossmann@ipvs.uni-stuttgart.de, wieland@iaas.uni-stuttgart.de

Abstract*. The world of spatial data is split into individual data source islands that have different thematic or spatial focuses. When attempting to integrate those data sources, severe challenges arise, since for most GIS application domains a spatial integration schema does not exist. This is also true for the newly emerging domain of mobile, context-aware applications. Since the users of these systems are mobile, transborder access to spatial data or context models is crucial for global deployment. The basis for this work is the Nexus Augmented World Schema, a conceptual schema that serves as an integration standard for autonomous spatial context servers. This paper analyzes some major spatial data standards, especially with respect to the requirements of a spatial integration schema for context-aware applications and illustrates the Nexus approach.*

1. Introduction

The world of spatial data is still split into individual database islands that have different thematic focuses, like e.g., topographic, cadastral, environmental, or traffic related databases. Some are only available for certain geographical regions, e.g., for a city, a federal state, or a country. Handling spatial data across administrative boundaries is rarely possible without difficulties. Hence, a joint use of the separate data islands is often not feasible. This is a big disadvantage regarding the use of GIS in today's decision processes. One of the main integration problems is the lack of a common data schema—which we call spatial integration schema here—that can provide a basis for data integration.

On the other side, a new application domain has emerged in research and industry: So-called context-aware (and often location-based) applications adapt their behavior depending on the situation of their user or the physical world (Schilit, Adams & Want 1994), e.g., navigation systems or ubiquitous computing environments envisioned by Weiser (1991). Common to these applications is their need for context information that

[1] This work was funded by the Collaborative Research Center *Nexus: Spatial World Models for Mobile Context-Aware Applications* (grant SFB 627).

can be used to derive the user's current situation. Depending on the application, such a context model contains various kinds of information. An analysis of different applications shows that their needs for data are overlapping. Common data types in context models are geographical context like digital map data, technical context like available devices or communication networks, information context like points of interest or documents relevant to the current place or situation, and dynamic context from sensors like mobile objects or weather data. By maintaining common context models and sharing them between applications we can significantly reduce the development and deployment effort of context-aware applications.

This paper is organized as follows: In Section 2, we illustrate the vision of a global, federated context model that can be achieved with a spatial integration schema. Section 3 covers related work. In Section 4, we analyze existing spatial data standards with respect to the criteria that were defined in Section 2.1. Finally, in Section 5, the Nexus Augmented World Schema (AWS), a conceptual spatial schema that solves the proposed problems is described.

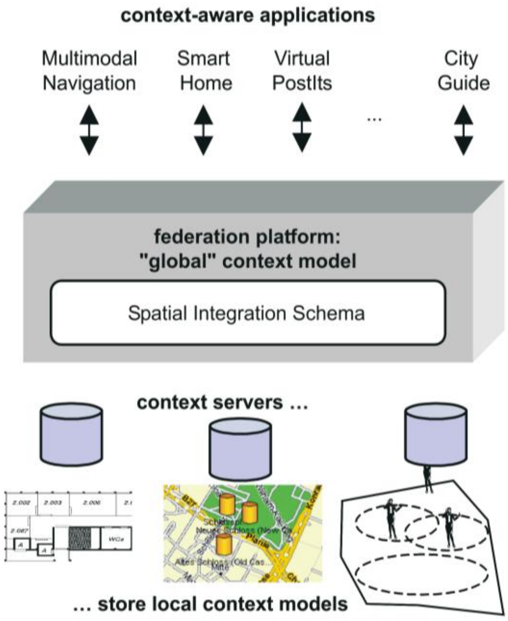

Figure 1. A global, federated context model

2. The Vision of a Global and Federated Context Model

The goal of the Nexus project is to support all kinds of context-aware applications through an open platform that efficiently manages large-scale context models. The platform is realized as a federation between so-called context servers that store local context models. This allows autonomous data providers keeping control of their context data. Using this platform we increase both the total amount of available information and the geographical scope. Figure 1 depicts the high-level architecture of a global context model. We assume that each context server has only data for a certain geographical region and of certain object types. Most of the data objects contain some spatial features.

To achieve this goal, we develop a federation platform that provides applications a single interface and an integrated view on the context data. One important problem that has to be solved is to find an integration schema that facilitates this task. The next section states important requirements or criteria that such an integration schema has to fulfill.

2.1. Criteria

The criteria listed below have been selected as the most important indicators that allow an answer to the question of the suitability of an existing standard for the requirements of global and federated context models:

Support for multiple representations: In a system integrating a large number of independent data providers, it is unavoidable that their data models overlap both by geographical scope and content. The result of a query, e.g., a selection of buildings within a given area may contain different representations of the same real-world object. The data schema should be able to represent this fact, and the system should provide a way to handle multiple representations, e.g., by merging them to a single object when possible.

Globally unique IDs and locators: Objects need some kind of unique ID in order to be referenced by applications. If a system supports merging different data sets from arbitrary sources, IDs for new objects have to be generated in a way that their global uniqueness is assured. Additionally, a federated system should provide some way for an application knowing only the ID of an object to retrieve the object itself, i.e., to determine the object's data provider.

Support for dynamic data: Most location-based applications do not only need static data like roads or hotels, but also dynamic data of moving objects like people or vehicles. Additionally, applications may require dynamic data generated by sensors. Thus, such objects must be modeled appropriately within the data schema and the system must be able to support these objects.

Defined schema semantics: To do anything useful with the data received, applications must know the semantics of the data, i.e., an application receiving an object of type 'building' has to understand what the data provider means with 'building'. The most simple (and most efficient) way to achieve this is to use defined schema semantics.

Schema extensibility: It is obviously impossible to define a global schema that fulfills all requirements of present and future data providers. Thus, the system has to provide a means to extend the schema dynamically. Existing applications, which do not support the schema extension, should nevertheless be able to make use of the data belonging to the schema extension in some way.

Conformity to OGC/ISO-TC211: The Open Geospatial Consortium (OGC) and the ISO-TC211—which are meanwhile closely coupled—published standards for geodata schemas and exchange languages. While they may not be suitable for all applications, embedding parts of them in other systems where feasible may increase interoperability of those systems.

Internationality: Some of today's geodata schemas are specifically tailored to administrative structures of the country they were originally designed for. This is a major disadvantage for a system of global extent, as converting spatial data from other countries is very difficult and usually leads to some loss of information. Ideally, the system would provide a basic schema, which reflects the most important features for all countries and which allows some kind of extensibility to be able to represent more specific features.

Supported types of application: Some geodata schemas were designed with a specific application in mind. Using those schemas in different application domains is usually difficult or even impossible. Again, an ideal schema would provide the capability to model the basic aspects relevant to most applications while being extensible for more specific requirements.

Representing history and prognosis: Applications like traffic jam prognosis or a city guide integrating historic data require the data schema to be able to simultaneously represent the different states of an object at different times in order to deduce the evolution of an object. Additionally, also propositions of an objects' future behavior must be possible.

3. Related Work

Information integration systems have been a research topic for many years. Today, commercial enterprise application integration (EAI) products like IBM's DB2 Information Integrator (Bruni 2003) as well as some research prototypes like TSIMMIS (Garcia-Molina et al. 1997) focus on integrating a previously known fixed set of data sources and on developing an integrated schema for these sources. The area of schema integration (Batini, Lenzerini & Navathe 1986) as well as software systems for this purpose, e.g., Clio (Miller et al. 2001), have a similarly restricted focus as they address the problem of transforming a fixed set of source schemas (and associated data) into an optimally calculated or predefined target schema. They lack the flexibility to handle dynamically changing sets of data providers and they do not aim at semantically integrating the data of different providers. EAI and schema integration software can be used locally to transform the data of a provider into a common domain schema compliant representation. Additionally, none of these approaches takes the special characteristics of spatial data into account.

In the field of GIS, approaches to overcome semantic heterogeneities between different application domains or user communities, respectively, have been made using ontologies or semantic mappers (translators). For example, Fonseca, Egenhofer, Agouris & Câmara (2002) presented an architecture for Ontology-Driven GIS (ODGIS) where objects can be extracted from geospatial databases according to ontological criteria like roles, functions or constituting parts which are stored for each object type. Bishr, Pundt & Rüther (1999) proposed a method that uses domain-specific interfaces in order to map spatial data from one community's ontology (e.g., topography-centered) to the ontology of another one (e.g., transportation-centered). Cruz, Rajendran, Sunna & Wiegand (2002) also used an ontology-based approach in their system. Queries are posed against a global schema (the ontology) and are rewritten by the query processor with the aid of expert-provided agreement files, which describe the mapping between the global and the local schema. A specific problem of information integration – the problem of multiple representation databases – was discussed by Balley, Parent & Spaccapietra (2004). The authors present the situation in France where they have three coexisting spatial databases containing the same real world objects. It is shown how these multiple representations can be modeled in a global geospatial data schema that allows global querying and ensures global consistency. None of the approaches in the

GIS domain has up to now been dealing with integration issues for global, context-aware applications. The modeling of different types of context and the federation of context models have not been tackled as well.

The GIS mediation system proposed by Boucelma, Essid & Lacroix (2002) integrates data coming from a set of Web Feature Servers (WFS). The WFSs can use different local schemas; the mediation system uses a global-as-view approach to integrate the schemas. While this approach simplifies rewriting the queries for the WFS by the mediation systems, it partly exposes the schema heterogeneity to the applications. Adding new WFSs usually require changes of the global schema, which limits the scalability of this approach with respect to the number of data sources.

Finally, a number of integration frameworks for context-aware applications have been developed over the last years. Barretto & da Silva (2004) give a good overview of these approaches and proposes an own approach. This work focuses on system integration in ubiquitous computing. In contrast, we focus in this contribution on the data modeling and data integration, particularly for spatial data models.

4. Existing Spatial Data Standards

Spatial data standards have been defined by different institutions all over the world either from different application perspectives or as a general fundament for different kinds of applications. Basically, they can be divided into international standards specified by global standardization organizations and national standards defined by individual countries for their specific purposes. Both types of standards shall be considered in the following sections.

In the last decade, efforts have been made by the Open Geospatial Consortium (OGC) and the International Standards Organization (ISO) in close collaboration to achieve interoperable GIS on an international level. Up to now, mainly technical interoperability issues were taken into account and as one of the main results the Geography Markup Language (GML) was developed (Portele 2007). However, semantic interoperability is a topic that has not been addressed sufficiently by standardization organizations although its importance has been recognized. The OGC has also started an initiative called OpenLS (Open Location Services) that mainly specifies services useful for location-based applications but does not provide a detailed model of the world.

Another spatial data standard of international relevance which was originally invented by the industry and meanwhile has become an ISO standard as well is the Geographic Data Files Format (GDF) (ISO 14825:2004). It was developed for the purpose of car navigation systems.

There are also country-specific standards which are driven by national organizations like the Federal Geographic Data Committee (FDGC) in the United States or the Spatial Information Council for New Zealand and Australia (ANZLIC). They are aiming at the development of geospatial data infrastructures. In Germany, the Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany (AdV) has established national standards, namely ATKIS (Authoritative Topographic Cartographic Information System) and ALK (Automatic real estate map). ATKIS and ALK are being transformed into a universal data schema for all kinds of authoritative surveying data of Germany, called the AFIS-ALKIS-ATKIS reference model (AFIS: reference point information system, ALKIS: Authoritative real estate information system) by which the object definitions within the separate schemas of ALK an ATKIS are harmonized (Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany 2008). Another standard called CityGML is just evolving in Germany. It has been initiated by the Special Interest Group 3D of the spatial data infrastructure project of North Rhine-Westphalia and defines an application schema based on GML to represent 3D city models at different levels of detail (Kolbe, Gröger & Plümer 2005).

4.1. Evaluation of Existing Standards

In this section we discuss to which degree the available standards meet the needs of a spatial integration schema for context-aware applications. This kind of evaluation is sometimes ambiguous and difficult to do. Thus we set up 4 categories to express tendencies for the suitability of a standard for the respective task/requirement: Impossible/ not supported: – ; partially (but not entirely) possible/supported: (–); possible/supported using work-arounds: (+); possible/supported: +.

The results of the evaluation are presented in Table 1. The last column of Table 1 contains the evaluation of the Augmented World Schema (AWS) which is discussed in Section 5.

Multiple representations / geometries. Typically, no existing standard can express that two data objects in different data sets represent the same real world entity. Hence, multiple representations cannot be described by existing standards at all, and they always exist separately, without knowledge of each other. However, at least in ATKIS and AAA, an object of the real world can be represented by different geometries, e.g., a place can either be defined as a point or as an area. Also in CityGML, due to its level of detail approach, an object can be represented by different geometries, e.g., only as a cuboid or as a detailed 3D object with roofs etc. On the other hand, GDF data are only captured in approximately the same scale and its objects cannot contain multiple geometries.

Globally unique ID. AAA, ATKIS and GDF are aiming at system-wide unique IDs whereas ALK and CityGML do not provide mechanisms supporting this feature. None of the schemas offers locators, i.e., a concept by which an object can be found within a distributed system when the identification of the object is known.

Support for dynamic data. GDF, as well as all the other presented standards, does not contain structures for dynamic or mobile objects and temporal relations, i.e., cars, pedestrians, etc. and chronologies expressing what happened before, during or after a certain event cannot be represented in schemas of existing standards.

Defined schema semantics. Except ALK, which does not have a strong semantic description behind it, all of the presented standards do have a fixed schema thoroughly defining the properties of the comprised objects.

Schema extensibility: Currently, only CityGML supports application specific extensions due to its GML origin. All other spatial data schemas do not foresee to extend the existing classes. E.g., introducing mobile objects or footpaths within GDF, ALK or ATKIS would result in non-standard specific extensions which could not be used by other applications. Instead, such changes of the original data schema would only be realizable by tedious standardization processes.

Table 1. Evaluation of existing spatial data standards

Requirements/Standards	ATKIS	ALK	GDF	AAA	CityGML	AWS
Multiple representations	–	–	–	–	–	(+)
Multiple geometries	(+)	–	–	(+)	+	+
Globally unique IDs	(+)	–	(+)	(+)	(–)	+
Support for dynamic data	–	–	(–)	(–)	–	+
Defined schema semantics	+	(–)	+	+	+	+
Schema extensibility	–	–	–	–	(+)	+
Supported types of applications	(+)	–	(–)	(+)	(–)	(+)
Conformity to OGC/ISO-TC211	–	–	–	(+)	+	(–)
Internationality	–	–	(+)	(–)	(+)	(+)
History and prognosis	–	–	(–)	(+)	(–)	(+)

Supported types of application. Adapting existing standards to multiple applications is hardly achievable. With respect to the requirements of global context models for context-aware applications (e.g., for performing intermodal navigation where a user can traverse multiple networks like roads as well as public transportation lines and pedestrian paths), GDF is too much restricted to road data and does—at the current stage—not contain essential object classes, at least not in necessary detail. The same is true for ALK, ATKIS, AAA and CityGML. Although ATKIS and AAA show more comprehensive conceptual schemas that were developed as a basic schema for the representation of topographic objects being able to support diverse applications, they are still lacking some object classes necessary for context-aware services like sensors. Furthermore, for one important context aware application—navigation—ATKIS and AAA data are not suitable: Information about how roads can be traversed or about driving limitations (forbidden maneuvers) is missing.

Conformity to OGC/ISO-TC211. The central standardization organizations for spatial data are OGC and ISO-TC211. Up to now, semantic interoperability has not been tackled sufficiently by OGC/ISO, but at least important technical obstacles have been overcome that should be adopted by the GIS community. Since ATKIS and ALK are standards which were developed at the beginning of the 80s, they of course do not consider international standardization issues. However, the AAA model uses only OGC or ISO definitions to represent the geometries of its objects and GML to exchange the data. GDF, although heading towards X-GDF where things are planned to be changed (e.g., it is intended to extend the schema to be able to perform pedestrian navigation and to represent 3D city models or to adjust the schema to OGC/ISO standards) (van Essen & Hiestermann 2005), currently does not adhere to OGC/ISO-TC211 guidelines.

Internationality. Since ALK, ATKIS and AAA are restricted to Germany, they can only be regarded as national standards without global relevance. In contrary, GDF includes internationalization issues, e.g., different address formats for different countries. CityGML also defines rather general object structures which can be used all over the world for the modeling of urban areas.

History and prognosis. Different temporal states of objects can only be expressed appropriately by the AAA reference model as it proposes a versioning concept which allows storing different versions of an object within an object container and so object histories can be reconstructed. GDF allows time-dependent attributes of objects. CityGML does not support different temporal representations besides those that can already be handled by GML. ATKIS and ALK are completely neglecting this issue. None of the schemas presents features to describe future states of an object derived by simulation or prognosis algorithms.

As a result of the evaluation, we found that no existing spatial data standard can be used to realize global and federated context models without facing significant drawbacks. Hence, we set up an integration scheme that optimally supports the domain of context-aware applications in such an environment: the Augmented World Schema.

5. Our Solution – The Augmented World Schema

The Augmented World Schema (AWS) is an object-oriented, common data schema used by context servers, the Nexus federation and context-aware applications to exchange and process data (Nicklas & Mitschang 2004). A fixed set of classes (the Standard Class Schema (SCS)) comprises those classes we consider basic for most context aware applications. Figure 2 shows an excerpt of the SCS on the left.

Object classes of the AWS are modeled in a class hierarchy. All spatial objects inherit from the basic object class SpatialObject which ensures that every AWS object has a unique identifier (the NOL, see below) and a geographic position. Additionally, every AWS object has a special attribute called type, which contains the name of the object class. With that, the object class can be queried like any other attribute of the object. The AWS offers some flexibility that extends the standard object-oriented approach: Many attributes are marked as optional, i.e., providers may choose to supply those attributes or not, but if they are supplied, their name and semantics are defined. The middleware expects that every application is able to handle SCS objects.

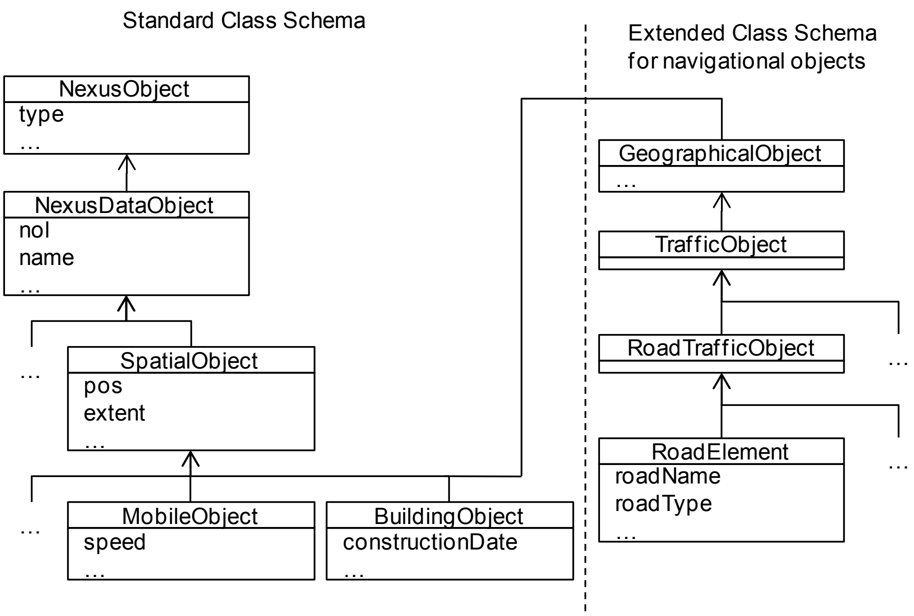

Figure 2. Standard Class Schema and an Extended Class Schema

The data of the AWS (i.e., the Augmented World Model) is not materialized at the federation tier but is distributed across the data providers. For this, we use the concept of Augmented Areas (AA) which corresponds to a certain geographical region and is associated with the SCS and optionally with one or more extended class schemas. The regions of different AAs may overlap each other.

5.1. Realization of Requirements

In the following, it is depicted how the criteria that have been set up in Section 2.1 as the basic requirements for a spatial integration schema are realized by the AWS:

Multiple representations. Since Augmented Areas can be overlapping both in space and in content, the AWS has to allow multi-represented objects. By means of explicit relations called MultiRepresentational Relations (or MRep Relations in short), multiple representations can be linked and made aware of each other (Volz & Walter 2004). As MRep Relations refer to a spatial location that can be derived from the geometries of the related objects, they can be spatially indexed and stored on regular, spatially-enabled context servers within Nexus. The concept of MRep Relations enables integration processes carried out by the federation component. This shall be illustrated by means of an example: If a client query requests street data for a certain geographical region and this request cannot be satisfied by one single Augmented Area alone, integration mechanisms are triggered on the federation level. This involves two steps: First, the street data of the two Augmented Areas plus the MRep Relations for those objects in the overlapping area which are multiply represented have to be loaded from the appropriate context servers. Secondly, the federation can merge the multiple representations into combined objects by exploiting MRep Relations (Volz & Bofinger, 2002). First approaches have been implemented here which geometrically adjust the data based on rubber-sheeting techniques and produce an average geometry from the two source geometries based on a triangulation. The result of a merge operation can be an object that has multiple types and multiple instances of the same attribute.

Globally unique ID. Each object in the Augmented World model has an attribute called Nexus Object Locator (NOL), which can be used both for identifying an object and finding the server where the object is stored. The NOL consists of three main parts: the object ID, the Augmented Area ID (both are globally unique) and a service description containing information on the service hosting the object (e.g., a web service). If two objects have the same object ID, they are considered to be representations of the same real-world entity (like having a MRep relation). This can be used to deliberately distribute different aspects of one object to different context servers, e.g., to optimize the management of the dynamic and the static parts of a mobile object (Grossmann, Bauer, Hönle, Käppeler & Nicklas 2005). Also, a data provider that wants to offer additional information to a given data set of another provider can use the object IDs of that provider for its own data objects (e.g., to add sightseeing information to given map data).

Support for dynamic data. The AWS contains static, dynamic, and mobile data objects. For the modeling, there is no difference between static and dynamic data: Both can be modeled as attribute values of AWS objects. However, a meta data concept (Hönle et al. 2005) allows representing additional information for a certain datum. This is especially designed for handling dynamic data, where meta data like time stamps, accuracy, update rate etc. are needed by applications. Mobile objects often change the data value of their spatial attributes (i.e., position), which is one of main selection criteria for data objects in that application domain. This afflicts both the data management and the applications. Therefore, the AWS models mobile objects in an own hierarchy (i.e., all mobile objects inherit from the class 'MobileObject').

Common schema semantics. This aspect is covered by class schemas. The identification of required object classes for the AWS has been based on a use case analysis for context-aware applications on the one hand and on the other hand on an analysis of existing (external) conceptual schemas. For these external schemas, we developed matching techniques in order to identify semantically corresponding object classes amongst them (Volz 2005) and applied mechanisms to integrate these object classes into the global schema. For example, in the case of existing conceptual schemas for street data, we established very basic object classes in the AWS like JunctionElement, RoadElement, DirectedRoad, etc. and neglected the complex data structures available in existing schemas for street data. Thus, we were able to develop mapping functions in order to transfer street data from existing databases into object classes provided by the AWS, i.e., the context servers of Nexus can easily be enriched by existing geospatial data applying these mapping functions.

Schema extensibility. By means of Extended Class Schemas, additional types can be introduced in the AWS, as shown in Figure 2 (on the right). If multiple applications share this knowledge, they have again a common schema semantic. The SCS may be extended by so called Extended Class Schemas (ECS). The object types of the ECS can inherit from any type in the SCS. ECSs may be defined anytime by any provider, so they are not necessarily known to all applications or to the middleware. We address this problem by two different approaches: First, applications specify with each query the ECS they know about. If the result of the query contains an object whose type belongs to a different ECS, it gets cast into the closest class of the SCS. And secondly, the middleware is able to extract information from structures it does not know completely.

Supported types of applications. The AWS is designed to support all kinds of context-aware applications, with an emphasis on location-awareness. However, most of the classes define objects of the real world with rather common attributes. Hence, data from the AWS can be used for other application domains needing spatial data.

Conformity to OGC/ISO-TC211. For several reasons, AWS is no GML Application Schema—we found that some of the concepts of a feature did not match the requirements of the AWS, especially with regard to multiple representations. However, for representing spatial and temporal data types, we use GML schemas.

Internationality. Since Nexus is designed as a global spatial information platform, we strived for an international design. However, we are aware that different cultures do have different views on the world. Therefore, the modeling of the AWS fits best in the western world.

History and prognosis. By means of the already mentioned meta data, timestamps and other temporal information can be added to the data objects and attribute values. The query language also provides temporal predicates to use this information to select and restrict result sets which already allows querying past states of the Augmented World Model. In the future, we plan to use data warehouse and data mining techniques to exploit this information for prognoses, e.g., in traffic analyses.

5.2. System Support

For supporting context-aware applications, developing a data schema only is not sufficient, a system for maintaining the data is also necessary. In large-scale scenarios, simple approaches like storing all the data on a single web server are not feasible. Instead, a distributed infrastructure is necessary, which on the one hand allows disseminating the data across many different servers and on the other hand provides a homogenous, integrated view of the data to the applications. The Nexus system (Nicklas et al. 2001) provides a proof-of-concept implementation fulfilling the requirements proposed in Section 2.1 using a three-tier architecture.

6. Conclusion

In order to realize the federation of context models in distributed environments with heterogeneous sources, a spatial integration schema has to exist. In this paper, we defined the basic requirements that such a schema has to conform to. Since context models are mainly organized in a spatial manner, we investigated existing spatial data standards and matched them against the defined requirements. We found out that—although we analyzed different types of standards—none of them was optimal since they were all designed from different viewpoints and were targeted to accomplish other tasks. As a consequence, we set up an own schema definition which conforms to existing standards as far as possible but on the other hand provides necessary extensions to support federated context models.

References

Balley, S., Parent, C. & Spaccapietra, S. (2004). Modelling geographic data with multiple representations. *Intl. Journal of Geographic Information Systems 18*(4), *pp. 327-352*

Batini, C., Lenzerini, M. & Navathe, S.B. (1986). A Comparative Analysis of Methodologies for Database Schema Integration. *ACM Computing Surveys, 18*(4)

Barretto, S., & da Silva, M.M. (2004). Using Integration Frameworks for Developing Context-Aware Applications. *Proc. of the 2nd European Symposium on Ambient Intelligence (EUSAI), LNCS 3295, Springer-Verlag, pp. 100-111*

Bishr, Y.A., Pundt, H. & Rüther, C. (1999). Proceeding on the road of semantic interoperability—Design of a semantic mapper based on a case study from transportation. *Proc. of the 2nd Intl. Conference on Interoperating Geographic Information Systems, Zurich, LNCS 1580, Springer-Verlag, pp. 203-215*

Boucelma, O., Essid, M. & Lacroix, Z. (2002). A WFS-based mediation system for GIS interoperability. *Proc. of the 10th ACM Intl. Symposium on Advances in Geographic Information Systems, ACM, pp. 23-28*

Bruni, P. (2003). Data federation with IBM DB2 Information Integrator V8.1. *IBM, International Technical Support Organization*

Cruz, I., Rajendran, A., Sunna, W. & Wiegand, N. (2002). Handling semantic heterogeneities using declarative agreements. *Proc. of the 10th ACM Intl. Symposium on Advances in Geographic Information Systems, ACM, pp. 168-174*

Fonseca, F., Egenhofer, M., Agouris, P. & Câmara, G. (2002). Using ontologies for integrated geographic information systems. *Transactions in GIS 6*(3)*, pp. 231-257*

Garcia-Molina, H., Papakonstantinou, Y., Quass, D., Rajaraman, A., Sagiv, Y., Ullman, J. D., et al. (1997). The TSIMMIS approach to mediation: data models and languages. *Journal of Intelligent Information Systems 8*(2)

Grossmann, M., Bauer, M., Hönle, N., Käppeler, U., Nicklas, D. & Schwarz, T. (2005). Efficiently managing context Information for large-scale scenarios. *Proc. of the 3rd IEEE Intl. Conference on Pervasive Computing and Communications, IEEE Computer Society, pp. 331-340*

Hönle, N., Käppeler, U., Nicklas, D., Schwarz T. & Großmann, M. (2005). Benefits of integrating meta data into a context model. *Proc. of 2nd IEEE PerCom Workshop on Context Modeling and Reasoning, IEEE Computer Society*

Kolbe, T. H., Gröger, G. & Plümer, L. (2005). CityGML—Interoperable access to 3D city models. *Geo-Information for Disaster Management (GI4DM), Springer-Verlag*

Miller, R.J., Hernández, M.A., Haas, L.M., Yan, L., Ho, C.T.H., Fagin, R. & Pope, L. (2001). The Clio Project: Managing Heterogeneity. *ACM Press, SIGMOD Rec. 30*(1)

Nicklas, D., Großmann, M., Schwarz, T. Volz, S. & Mitschang, B. (2001). A Model-Based, Open Architecture for Mobile, Spatially Aware Applications. 7th Intl. Symposium on Advances in Spatial and Temporal Databases (SSTD)

Nicklas, D. & Mitschang, B. (2004). On building location aware applications using an open platform based on the Nexus Augmented World Model. *Software and Systems Modeling*, *3*(4)*, pp. 303-313*

Portele, C. (2007). OpenGIS Geography Markup Language (GML) Encoding Standard, Version 3.2.1. *http://portal.opengeospatial.org/files/?artifact_id=20509*

Schilit, B.N., Adams, N. & Want, R. (1994). Context-aware computing applications. *IEEE Workshop on Mobile Computing Systems and Applications, IEEE Computer Society*

van Essen, R. & Hiestermann, V. (2005). "X-GDF" — The ISO Model of Geographic Information for ITS. *ISPRS Workshop on Service and Application of Spatial Data Infrastructure, XXXVI(4/W6)*

Volz, S. & Bofinger, J. (2002). Integration of spatial data within a generic platform for location-based applications. *Proc. of the Joint Intl. Symposium on Geospatial Theory, Processing and Applications*

Volz, S. & Walter, V. (2004). Linking different geospatial databases by explicit relations. *Proc. of the XXth ISPRS Congress, Comm. IV, pp. 152-157*

Volz, S. (2005). Data-driven matching of geospatial schemas. *Proc. of the 8th Conference on Spatial Information Theory (COSIT), LNCS 3693, Springer-Verlag, pp. 115-132*

Weiser, M. (1991). The computer for the 21st century. *Scientific American, Sep. 1991*

Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany (2008). Documentation on the modelling of geoinformation of official surveying and mapping in Germany (GeoInfoDok), Version 6.0