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DISTRIBUTED SPATIO-TEMPORAL MODELING AND SIMULATION

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ABSTRACT

The objective of upcoming research in the field of geo-processing is to evolve interoperability standards to develop flexible and scalable controlling and simulation services. In order to overcome the limitations of proprietary solutions, efforts have been made to support interoperability among simulation models and geo information systems (GIS). Existing standards in the domain of spatial information and spatial services define geoinformation (GI) in a more or less static way. Though time can be handled as an additional attribute, its representation is not explicitly specified. In contrast, as the standard for distributed heterogeneous simulation, the High Level Architecture (HLA) provides a framework for distributed time-variant simulation processes but HLA is lacking in supporting spatial information. A web-based *D*istributed sp*A*tio-tempora*L* *I*nteroperability architecture DALI integrating these initiatives will be presented here. The long term goal of this DALI Architecture is making *standardized* off-the-shelf GI and simulation services usable for highly specialized simulation and controlling applications.

1 INTRODUCTION

Simulation is the key technology for describing, assessing, analyzing, forecasting, etc. the dynamics of real, planned or virtual processes or systems. Often these processes operate both in time and space. Typical examples are traffic and logistic systems, environmental processes like floods or emergency management systems etc. (Klein 20001).

The spatial dimension can be of 2D or 3D type as in terrain or earth surface modeling where height or depth matters. Spatial information is used to describe, analyze and visualize simulated objects' geometrical and topological aspects such as line-of-sight calculation, neighborhood relationships, and influence of environmental impacts.

Therefore, the explicit support of spatio-temporal aspects is an issue in simulation science. Topics such as standardization, interoperability and consistency (esp. among distributed spatially aware simulations operating in the same spatial context) have to be addressed.

The description and analysis of spatio-temporal processes is one of the core tasks in geo-sciences too. The development of GI technological tools suited for this task belongs to the traditional research and development foci of geoinformatics. Based on this background, the following main research tasks exist:

- the conceptual description of spatio-temporal phenomena (Frank 1998),
- the extension of data models and (temporal) query languages mainly for the dynamic amendment of spatial data in time (concept of amendment; Peuquet 2001),
- the coupling of GIS with visualization systems for exploration of spatially and dynamically variant processes (Uhlenküken and Schmidt 2000),
- and the coupling of GI components with simulation systems.

The integration of heterogeneous software systems capable of simulating, capturing and controlling spatio-temporal processes for operational purposes is difficult as well as cost and time intensive (Bernard 2001). The reasons for this are mainly the monolithic software and system architectures and the proprietary interfaces of the systems to be integrated. Methodological integration problems resulting from the necessary holistic description of temporal and spatial aspects as well as the synchronization of distributed spatio-temporal models (while preserving causality) have prevented common integration standards up to now.

The advantages of a software development process based on standardized, interoperable and reusable components cannot be exploited. Software plug&play on the user side across system, software and platform boundaries is not realizable today.

Interoperability approaches in both the geoinformation domain and the simulation domain have led to developments, architectures and standards which support and ensure interoperability of software components and services on a medium and long term basis at least in the respective domain. These initiatives are discussed with respect to their mutual integrability. A software architecture is drafted which uses web-based integration services to bring together the two most interesting state-of-the-art interoperability standards of the GI and simulation domain.

Based on a brief discussion of the need for interoperability and emerging interoperability approaches, the following sections introduce a web-based service architecture to integrate distributed heterogeneous GI and simulation services. In the following, the term "simulation" is understood in a broader sense and explicitly includes real-time applications such as offering geoscientists the possibility to be an active part of the simulated scenario. The given approach is a further development of the service architecture presented in (Bernard et al. 2001b). Results include prototypical implementation of a complex, distributed hydrological simulation system to forecast spatially distributed runoff.

2 NEED FOR INTEROPERABILITY

Ongoing research concerning the analysis of spatio-temporal processes in, for instance, environmental, socio economic or cadastral applications focuses on the following main topics:

- Differentiation of different concepts to describe spatio-temporal processes e.g. (Frank 1998, Hornsby and Egenhofer 2000),
- Representation of spatio-temporal processes in data models and development of suitable query languages, e.g. (Voigtmann 1998, Erwig et al. 1999, Peuquet 2001, Spéry et al. 2001),
- Linkage of spatio-temporal simulation models with GIS e.g. (Fedra 1996, Takeyama and Couclelis 1997, Duane et al. 2001),
- Visualization and Exploration of dynamic spatial processes e.g. (Yuan 1998, Uhlenküken and Schmidt 2000).

First steps to integrate some of the emerging solutions to the aforementioned topics have been completed. As regards system integration, the use of interoperable components is a key technique (Bernard and Krüger 2000). Well-designed interoperable simulation and analysis components offer the freedom to choose the components best suited for different specific areas of application and to avoid tedious data conversions. Designing interfaces on a higher level of abstraction allows standardization approaches to integrating systems of various areas of applications and thus increasingly supporting interdisciplinary applications. Assuming that interoperable components, which manage and analyze spatial-temporal information, require a common conceptual model of space and time, basic semantic aspects extend the level of technical interoperability.

However, recent approaches to handling dynamic spatial processes provide possibilities either to post-assess measured and modeled spatio-temporal information or to pre-assess spatio-temporal results of prognostic or scenario simulations. A more flexible approach is needed here. Spatio-temporal data, such as a four-dimensional scenario description, has to be managed, independent of its position on the (real or virtual) time axis. It might be stored as:

- historical data such as recorded process data monitored in the past,
- (near) real-time data using sensor networks or other data sources and,
- fictitious or prognostic decision support data generated by appropriate simulations.

In terms of reusability, there should be one generic way of handling these three types of spatio-temporal data in order to allow a broad range of application. Interoperability between simulation and non-simulation components (such as databases, sensor systems, etc.) is also needed here. Today, the integration of real-time measurements and controlling components is hardly taken into account by the GI community. Thus recent systems are more or less decoupled from the real world.

3 OPENGIS AND HLA AS INTEROPERABILITY STANDARDS

The objective of upcoming research in the field of geoprocessing is to evolve interoperability standards to develop flexible and scalable controlling and simulation services. In order to overcome the limitations of proprietary solutions, efforts have been made to support interoperability among simulation models and geo information systems. Although extensive and ambitious in and of themselves, these efforts have been limited to one domain. The issue of the interoperability of geoprocessing services and distributed simulation components particularly based upon standardization approaches has not been addressed yet.

The Open GIS Consortium (OGC) is developing an interoperability standard in the domain of spatial information and services (OpenGIS). A service model of loosely coupled geoinformation services (GI-services) defining a completely http-based infrastructure has been specified as a result of the recent OGC Web Map Testbed 2 (WMT-2). Essential services currently being specified and further developed in the Open Web Services Initiative (OWS-1) are the Web Registry Service for investigating GI services and spatial information, the Web Feature Service and Web Coverage Service for providing vectored and gridded geodata and the Web Map Service for visualizing spatial information. All web-services can be linked in the sense of a service chain. The fundamental concept for searching and integrating OpenGIS web-services in an ad hoc manner is the idea of service trading (Reference Model for Open Distributed Processing, ISO/IEC 10740). Each GI service is able to publish its capabilities in a standardized way (ISO 19119). The Web Registry Service collects the metadata and can be asked by a client service to search a suitable service. The registry responds to the client request by sending back the URL of an appropriate service. Afterward the client is able to interact with a service offering the desired capabilities (Figure 1).

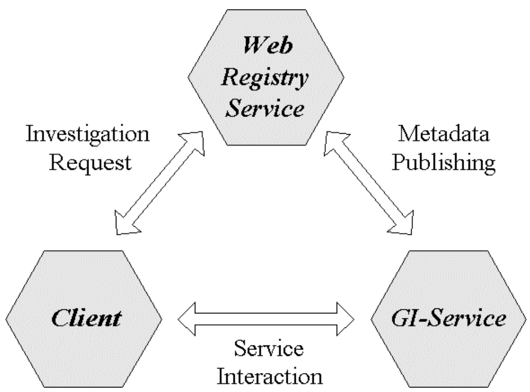

Figure 1: Service Trading

Yet the OGC still defines geoinformation in a more or less static way. Two example queries, taken from the current draft OGC specifications (OGC 2001a) and shown in Figure 2, illustrate how requests for a mapping service or a coverage service can be formulated using a 4-dimensional coordinate system. The query in example A asks for an animation to visualize a spatio-temporal process. Example B demonstrates a request for a file containing 4-dimensional data. Though time can be handled as an additional attribute (OGC 2001a), its representation is not explicitly specified (Bernard et al. 2001a). Thus it is impossible to model time-variant processes in a standardized interoperable way.

In contrast, the High Level Architecture (HLA), developed by the US Department of Defense (DOD 2001) and currently an IEEE standard (1516) (IEEE 2000), provides a framework for distributed time-variant simulation processes. The HLA is a federation approach and focuses on the interoperability and reuse of components. To facilitate interoperability, each member (federate) of a distributed simulation (federation) is equipped with appropriate interfaces to interact via a so-called runtime infrastructure (RTI), which provides basic services for data exchange, communication and inter-process synchronization (Straßburger 2001). The powerful time management service supports discrete and continuous time advancement mechanisms. The HLA is the state-of-the-art standard for distributed heterogeneous simulation. Civil prototypes exist, e.g. in the area of public transportation and manufacturing, but the HLA is lacking in supporting spatial applications

example A: *GetMap (movie loop at specified frame times):*

`VERSION=x.y.z`	`WIDTH=600`
`REQUEST=map`	`HEIGHT=300`
`LAYERS=ozone`	`TIME=2000-07-01/ 2000-07-31/P1D`
`SRS=EPSG:4326`	`ELEVATION=1000`
`BBOX=-180,-90,180,90`	`FORMAT=MPEG`

example B: *GetCoverage (4D block of data with dimension x,y,z,t):*

`VERSION=x.y.z`	`SKIPX=10`
`REQUEST=coverage`	`SKIPY=10`
`LAYERS=layer`	`TIME=2000-07-01/ 2000-07-31/P1D`

Figure 2: Two Example-Queries for Spatio-Temporal Data

Hence the shortcomings of OpenGIS and HLA discussed can be considered complementary. Therefore integrating both standardization approaches would offer a solid foundation for distributed spatio-temporal modeling and simulation. The approach described in this paper focuses on integrating standardized OpenGIS and HLA-based simulation services using web-based communication technologies.

HLA itself is not a web-based technology. The communication protocol underlying the interface definitions is not defined. Thus HLA/RTI software developers/vendors are free to implement their own communication routines. Nevertheless, with the free DMSO HLA/RTI software package as the reference, most of the HLA/RTI software is using TCP/IP as the underlying communication protocol, and some are even wire-compatible with the DMSO implementation.

This, of course, does not prevent HLA Federates from having a web-based interface or offering web-based services itself. The fact that HLA federates are usually only available during the runtime of a federation must be taken into consideration. This makes it difficult to make them part of a web-based service infrastructure (e.g. in the sense of OGC or UDDI), which normally presupposes permanent accessibility.

On the other hand, OpenGIS services do not have the HLA type of context over a certain period of time such as the runtime of the federation, the logical time axis within, etc. Table 1 provides a comparison of HLA and OpenGIS key features.

Table 1: HLA/OpenGIS Key Feature Comparison

Criteria	HLA	OpenGIS
Domain	Time	Space
Applications	Simulation	GIS
Approach	Distributed Heterogeneous Simulation-based Systems	Interoperable Geo-enabled Web-Services
Standardization	Yes DoD, NATO, IEEE	Yes OGC
Temporal Awareness	Yes	No
Synchronisa-tion/Time Man-age-ment (TM)	Yes Extensive TM In-teroperability	No
Spatial Aware-ness	No	Yes
Availability of Services	During Federation Runtime	Permanent
Web-based Services	Communication based on TCP/IP, no web-based ser-vices (Federates may have web in-terfaces)	Yes
Communication Style	Stateful	Stateless

An integration of both standardization approaches would offer features and services accessible to both basic architectures and would provide a solid foundation for an interoperability architecture for distributed web-based simulation in the sense of (Page and Opper 2000). The main objective is integrating heterogeneous web-services for spatio-temporal modeling and simulation. Following (Kreger 2001) and (OGC 2001a), a web-service is defined here as an interface that describes a collection of operations that are network-accessible through http-based URL-encoding.

The long-term goal of this approach is making *standardized* off-the-shelf GI- and simulation services usable for a broad variety of spatio-temporal simulation and controlling applications and providing a technological basis for increased multidisciplinarity between GI and applied modeling science.

4 ARCHITECTURE FOR DISTRIBUTED SPATIO-TEMPORAL INTEROPERABILITY (DALI)

The following proposes the DALI-Architecture (Distributed spAtio-temporaL Interoperability-Architecture), which results from redesign and refinement of the architectural approach presented in (Bernard et al. 2001b). This redesign phase is grounded in experiences made with a first simple prototype system that models a simplified courier service.

The High Level Architecture as well as the Basic Service Model introduced by the OGC Web Map Testbed 2 offers a great potential to build up an interoperability architecture to integrate spatial, temporal and spatio-temporal services. The most critical shortcoming is that OpenGIS web-services and HLA federates reside on different levels of abstraction. While OpenGIS web-services are permanently accessible, stateless and completely specified for end user tasks, the HLA specifications are much more abstract, describing simulation components that are only available during the simulation lifetime.

In order to benefit from the strengths and capabilities of both architectures, a framework that integrates both worlds has to solve the following tasks:

- Enabling the Exchange of Geoobjects between HLA Federates
  First, a geoobject model describing basic OpenGIS features (e.g. Simple Features, Simple Feature Collections and Coverages) based upon the HLA object model template (OMT) is needed. The OMT is a meta-model describing the structure of exchanged data. Since current RTI implementations leave the responsibility of marshalling data to the federates, appropriate encoding and decoding factories have to support the standardized exchange of OpenGIS-compliant geoobjects. Standardized exchange implies using the XML based Geo Markup Language (GML) (Cox et al. 2001). GML provides optimal decoding and encoding capabilities to transform geoobjects into byte streams, the interchange format typically required by the HLA. Federates publishing geoobjects in the aforementioned manner are called *Geofederates* (GF).
- Enabling the Use of OpenGIS Services within Federates
  Subclassing a Geofederate by extending its capabilities to access existing well-known OpenGIS-compliant web-services results in the definition of

OGCWrapperFederates (WF). Since the current OpenGIS service specification lacks a common service interface to describe services generically, the implementation of a number of different OGCWrapperFederates becomes necessary. However, the outcome of the ongoing WMT-2, especially the basic service model will provide more generic solutions in the future.

- Extract published Geoobjects from Running Federations
  In order to avoid proprietary specification enhancements to providing simulated geoobjects to external data sinks, it is makes sense to specify a generic service that subscribes to the geoobject root class and therefore to all kinds of published geoobjects within a federation. This *GeoobjectListenerFederate* (LF) will be equipped with an appropriate interface to serve as a data store for external geodata consumers.
- Making Geofederates permanently accessible
  Federates and Geofederates respectively exist only during a simulation or monitoring process. Hence, as opposed to common OpenGIS Web Services, they are not constantly accessible. This gap is filled by defining a *GeofederateWebService* (GFWS), which is a web service that basically controls a Geofederate aggregation containing Geofederates running in possibly different federations. It is permanently accessible and responsible for the initiation, controlling and destruction of Geofederates. GeofederateWebServices aggregating GeoobjectListenerFederates can be wrapped with OpenGIS-compliant web-service interfaces.
- Controlling Distributed Simulations
  To control distributed simulations in terms of HLA federations it is necessary to provide *Simulation Controlling Services* (SCS) to start, control and destroy federations. This is done by communicating with the corresponding GeoFederateWebServices to manage and access the required Geofederates. It provides simulation scenario management and facade interfaces for OpenGIS-compliant access, optionally a Web Feature Service interface, a Web Coverage Service interface or a Sensor Collection Service interface as described in (OGC 2002) prospectus. Extending the OGC specifications will make it necessary to provide data push mechanisms to allow continuous data flow between the Simulation Controlling Service and any desired client. Once having the ability to describe the capabilities of an OpenGIS compliant service in a generic way, it is also possible to specify interfaces that describe distributed HLA simulations as new OpenGIS services

Yet how is everything to be put together?

The key element is a http-based communication bus such as the WWW between the components. The component for Simulation Controlling Services (SCS) represents the HLA world. These services wrapped with OpenGIS-compliant interfaces provide accessibility to simulation results. The OpenGIS part is represented by the known components such as Web Feature Services (WFS), Web Coverage Services (WCS) and Web Mapping Services (WMS).

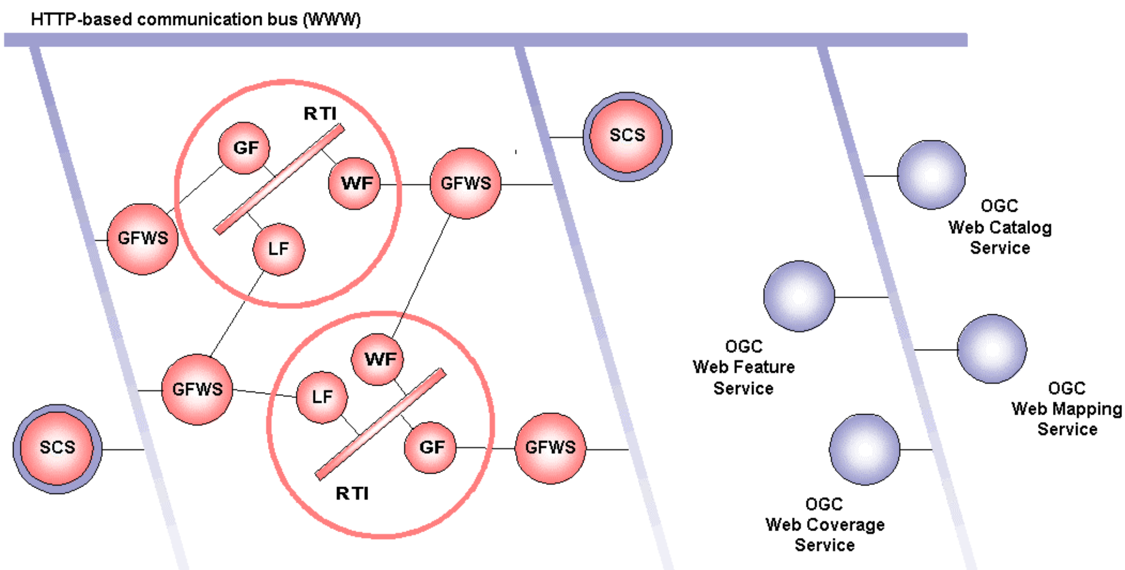

Figure 3: Functional Overview containing Geofederates (GF), GeoobjectListenerFederates (LF), GeofederateWebServices (GFWS), and Simulation Controlling Services (SCS)

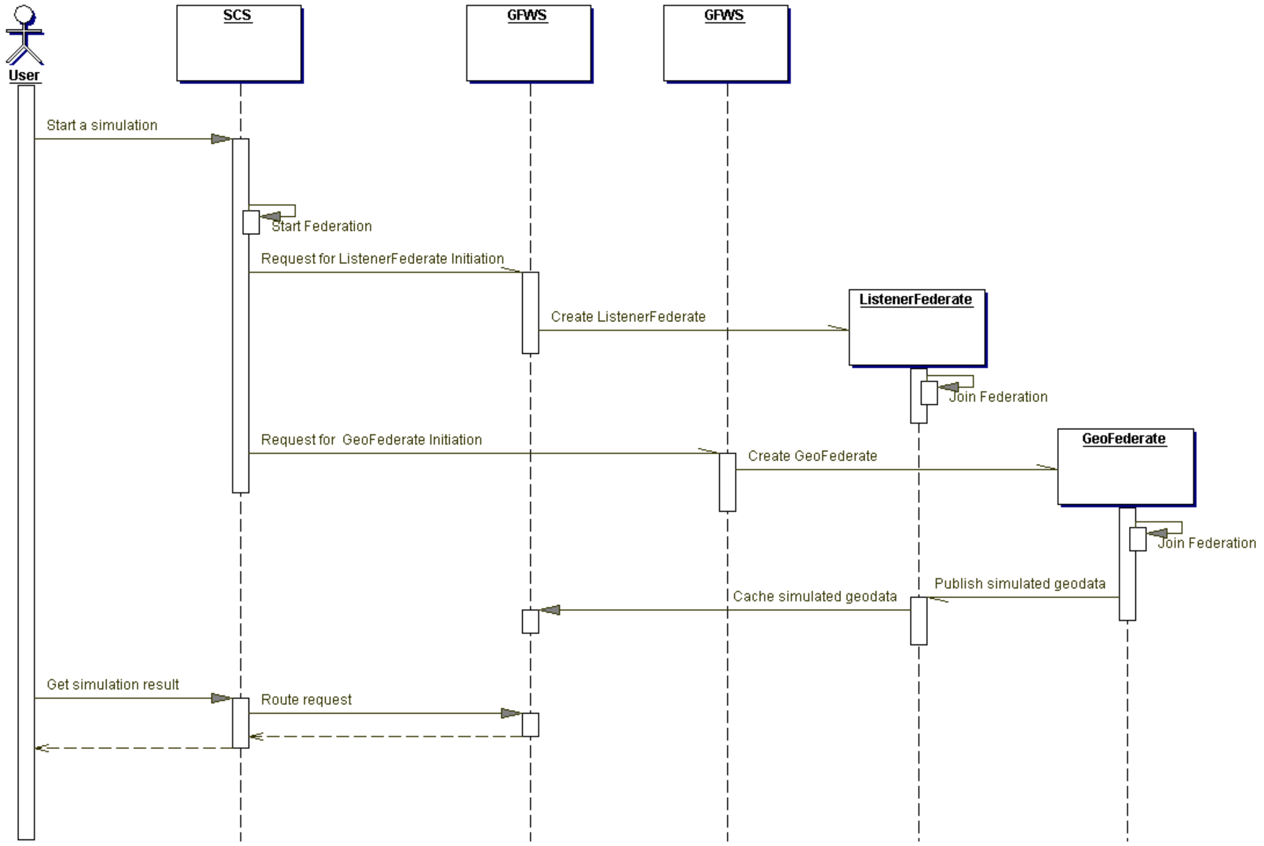

Figure 4: Sequence Diagram of Service Interactions

The interfaces of all components are completely based on URL encoding techniques. These Simulation Controlling Services interact with GeoFederateWebServices (GFWS) which again instantiate Geofederates (GF). The communication and synchronization of the *Geofederates* is done exclusively by the RTI. Based on these elementary services, it should be possible to specify a framework for spatio-temporal tasks. Figure 3 shows a functional overview of the DALI-Architecture.

The sequence diagram shown in Figure 4 illustrates the temporal progression of the service interactions described above.

5 APPLICATION SCENARIO

The interoperability architecture presented will be prototyped in an upcoming project by integrating a complex distributed hydrological simulation system to forecast spatially distributed runoff. In addition to a set of static spatial input data provided by OpenGIS Web Services, the simulation will be parameterized by extremely up-to-date rainfall data, provided by on-line measuring points which are integrated by appropriate Geofederates. Current runoff measurements are incorporated to continuously calibrate the model during runtime integrating water level measurement points. Interoperable sub-models can be integrated to forecast high water hazards and flood damage to supply suitable information for operative emergency management.

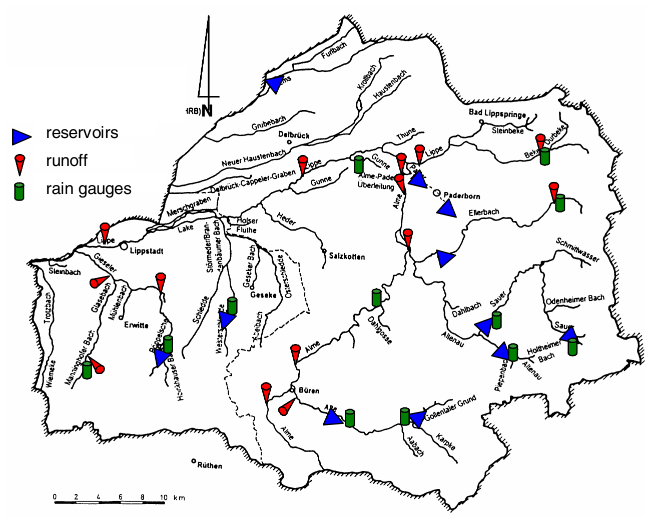

Figure 5: Case Study Region in Germany

The first prototype was developed to demonstrate the basic concepts described above and to serve as the platform for additional federates and spatio-temporal services. A case study region in Germany has been chosen that allows access to a (nearly) real-time sensor network in reservoirs and rain gauges. Figure 5 shows a map of the Case Study Region together with the locations of reservoirs, runoffs and rain gauges.

The hydrological model (shown in Figure 6) is based on the so-called SHE-model and is used by the hydrology federate.

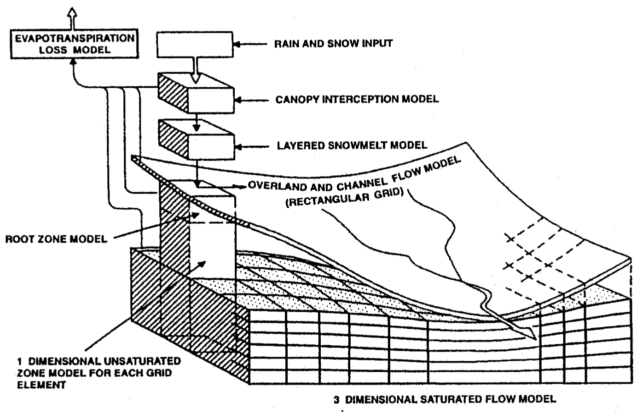

Figure 6: Hydrological Model (SHE-Model)

The prototype consists on the following components:

- The Sensor Federate
  The Sensor Federate provides (nearly) real-time rainfall data of the case study area. It is also capable of providing historic rainfall data based on recorded data stored in a database. It is able to act as a pacemaker for the rest of the federation. In terms of the framework described above, the sensor federate acts as GF.
- The Hydrology Federate
  The Hydrology Federate implements the SHE model (see Figure 6) and uses the rainfall and other data provided within the federation. It subscribes to the rainfall data and publishes the forecast which can be configured as different forecast scenarios. A 3 hour forecast of water levels has been used as default forecast scenario. In terms of the framework described above, the sensor federate acts as GF.
- The Observer Federate
  The Observer Federate subscribes to the sensor and the forecast data and stores it in a log file (database) in order to provide actual and historical sensor and forecast information to the observing components. In terms of the framework described above, the sensor federate acts as LF.
- The Sensor Collection Service
  Recently geocoded simulation results collected by the Listener Federate are logged in a geodatabase and made accessible in an OpenGIS-compliant manner by a Web Feature Service (WFS Version 0.0.13) and a Web Coverage Service (WCS Version 0.4). An important part of the ongoing OGC Open Web Service Initiative is to specify a Sensor Collection Service as part of the upcoming Sensor Web (OGC 2002). Sensor Collection Services will offer a mandatory interface to provide time variant measurement data which can be also utilized to provide simulation results. If a first specification draft will be available publicly, a Sensor Collection Service will replace the currently used WFS and WCS within the prototype application.
- Web Map Service
  To visualize spatial simulation results and make the visualization available to the OpenGIS community, the prototype application makes use of an OGC Web Map Service (WMS Version 1.1.0, OGC 2001b). A client application utilizes a WMS by sending a `getMap` request specifying the desired map layers, the spatial extent etc. The Web Map Service parses the request, retrieves the necessary geodata from underlying OpenGIS components WFS and WCS or cascades additional WMS, renders the retrieved geoinformation, generates an image and sends it to the client. The WMS developed for the prototype application is SLD (Styled Layer Descriptor)-enabled. This means, that rendering schemes for vectored and gridded data can be defined by the user or rather the client application.

Figure 7 shows the relations between the components above. The HLA-oriented components are additionally marked with HLA attributes.

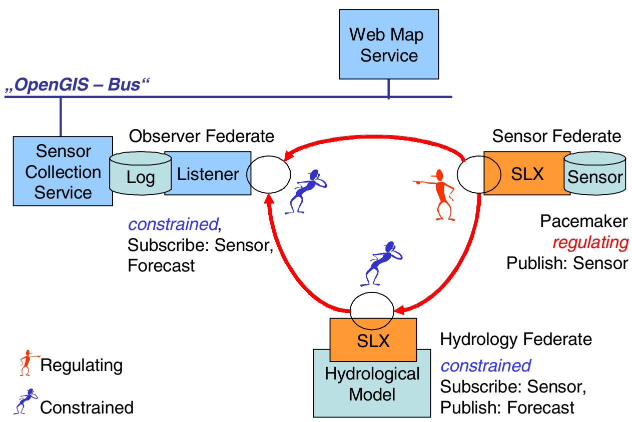

Figure 7: Functional Overview of the First OpenGIS/HLA-Prototype

6 CONCLUSIONS

The specifications of the OGC and the IEEE 1516 standards are a solid basis for specifying an interoperability architecture for distributed spatio-temporal simulation services (the DALI approach). First prototypes are available, and one has been described. It is necessary to incorporate the essentials of the DALI approach in the specification and standardization efforts of the OGC and SISO. First steps are being undertaken.

Next steps include a more generic specification of the integration services, especially concerning the Geofederate Web Service and the Sensor Collection Service (including web-based scenario management), and the development of permanent simulation services within the described framework.

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