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Spatio-temporal aggregation of European air quality observations in the Sensor Web

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ABSTRACT

An increasing amount of observations from different applications such as long-term environmental monitoring or disaster management is published in the Web using Sensor Web technologies. The standardization of these technologies eases the integration of heterogeneous observations into several applications. However, as observations differ in spatio-temporal coverage and resolution, aggregation of observations in space and time is needed. We present an approach for spatio-temporal aggregation in the Sensor Web using the Geoprocessing Web. In particular, we define a tailored observation model for different aggregation levels, a process model for aggregation processes and a Spatio-Temporal Aggregation Service. The presented approach is demonstrated by a case study of delivering aggregated air quality observations on-demand in the Sensor Web.

1. Introduction

An increasing amount of observations gathered by geosensor networks is published via standardized Sensor Web technologies to enable an ad-hoc integration of heterogeneous observations in different applications (Broering et al., 2011). As observations usually differ in their spatio-temporal coverage and resolution, aggregation of observations in space and time is needed. Moreover, due to the heterogeneity of these observations, aggregating them is also not trivial. The aggregations need to be performed by dedicated geoprocessing facilities. The Geoprocessing Web with its aim to provide common analysis and transformation of geospatial data into geospatial information is promising to realize spatio-temporal aggregation in the Sensor Web. Currently, data coming from the Sensor Web and Geoprocessing facilities are tightly coupled and only realized for specific scenarios. Though aggregated observations are already available on the Web through for instance weather portals (WetterOnline, 2011) or public observation portals (EEA, 2011), these observations are only aggregated in space *or* in time. An integrative approach for spatio-temporal aggregation is missing. Moreover, these aggregates cannot be calculated on-demand nor are they accessible on the web in standardized formats. In addition, metadata about provenance or aggregation methods is currently not available.

A comprehensive approach for spatio-temporal aggregation in the Sensor Web allowing a flexible integration of observations at a required aggregation level needs to be investigated. The approach has to be flexible to enable easy reuse, integration, and composition of existing aggregation methods. Also, it needs to allow for an on-demand aggregation. To allow retracing aggregated observations to original observations, the approach needs to provide machine readable metadata about the original observations and the aggregation processes. The main contributions of the paper regarding these requirements are as follows:

1. A data model for observations that can be used across different aggregation levels. This model also incorporates metadata about provenance and aggregation method (Section 3).
2. A process model for spatio-temporal aggregation (Section 4).
3. A web service architecture for aggregation of observations including the definition of the Spatio-Temporal Aggregation Service (STAS) (Section 5).

In our approach, we propose a Service-Oriented Architecture (SOA) for spatio-temporal aggregation of observations. As the Open Geospatial Consortium (OGC) provides well-defined encodings and service interfaces for both, the Sensor Web and the Geoprocessing Web, we are utilizing these standards in our approach. As a basis for our SOA, we define a tailored observation model and process model for spatio-temporal aggregation. The proposed SOA consists of Sensor Observation Services (SOS), the standard service for providing observations in the Sensor Web (Na and Priest, 2007), and the Spatio-Temporal Aggregation Service (STAS), which is defined as a profile of the Web Processing Service

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(WPS). The WPS provides the basic service interface for the Geoprocessing Web (Schut, 2007). In a case study, we demonstrate how our approach meets the requirements identified above by *temporally* aggregating hourly measurements of Ozone to daily maxima and by *spatially* averaging these maxima for each federal state in Germany.

The remainder of the paper is structured as follows: At first, we provide a brief overview on related work and background information (Section 2). We then describe the tailored observation model that can be used across different aggregation levels (Section 3). Afterwards, we present the process model for spatio-temporal aggregation (Section 4). In the next section, we describe how we provide these processes in the Sensor Web (Section 5). The implementation of the approach for an aggregation of air quality observations is presented afterwards (Section 6). Finally, we discuss our results and identify further research (Section 7).

2. Background

This section provides the related work. At first, we give an overview about spatio-temporal aggregation, which forms the framework for this work. Afterwards we provide background information about Geospatial Web Services including Sensor Web technology, the Geoprocessing Web and the Model Web. Geospatial Web Services have been identified as a foundation of this work to enable interoperability of spatio-temporal aggregation on the Web. They provide common means to build interoperable geospatial applications in the Web (Zhao and Di, 2010).

An *aggregation process* computes a single value, an *aggregate*, for a group of attribute values by means of an *aggregation function* (Jeong et al., 2004). The attribute values are grouped by a *partitioning predicate*. In our work, spatio-temporal aggregation combines objects in space and time and provides means to compute aggregates for certain attribute values attached to these objects. Most of the research on spatio-temporal aggregation during the last years has focused on improving aggregation operations in spatio-temporal databases. For example, Vega Lopez et al. (2005) give a comprehensive survey on spatio-temporal aggregation methods in databases. Others develop general models for space and time that can be used as a basis for spatio-temporal aggregation: Worboys (1994) defines a unified model for space and time and Camossi et al. (2003) introduce a multi-granular spatio-temporal data model. Jeong et al. (2004) define a generic algorithmic framework for spatio-temporal aggregation processes in databases. Related research regarding sensor observations deals with the aggregation of low-level sensor data to reduce the communication load from sensors to databases and clients. For example, Madden et al. (2002) introduce a tiny aggregation service for in-network aggregation of observations. However, in the case of low-level sensor data aggregation, observations with a higher resolution are usually lost. This is in contrast to our approach which provides flexible spatio-temporal aggregation of sensor observations to different aggregation levels in the Web.

Geosensor networks are interconnected sensors for monitoring environmental phenomena or geographic processes (Nittel and Stefanidis, 2005). The Sensor Web thereby abstracts from low-level interfaces and protocols in geosensor networks by adding an additional application layer in the Web (Broering et al., 2011). The Sensor Web Enablement (SWE) initiative of the Open Geospatial Consortium (OGC) aims to standardize the Sensor Web with a suite of standardized interfaces (Botts et al., 2007). The goal of the SWE initiative is to improve the interoperability of discovery, access and tasking of sensors in the Web. The Sensor Observation Service (SOS) forms the web-based interface for accessing observations and sensor metadata in the Sensor Web (Na and Priest, 2007). It allows client applications to query different kinds of observations through standardized operations and filters and retrieve the observations in a common format. The available observation data in the SOS can be retrieved in the Observations & Measurements (O&M) format, which is a model and encoding for observations (Cox, 2007a). Metadata about sensors that are registered at a SOS interface is provided in the Sensor Model Language (SensorML) (Botts and Robin, 2007). The observations can be queried in a flexible way from a SOS interface regarding space, time or thematic attributes. Though Havlik et al. (2009) introduce a system of cascading SOS instances, which is able to aggregate observations in time, an (spatio-temporal) aggregation functionality is currently not supported by the SOS interface. Following separation of concerns, aggregation *functionality* should be rather provided by other processing services and the aggregated observations should be accessible via the SOS interface.

In the past, most Geoprocessing functionality has been provided by monolithic Geographic Information Systems (GIS). By standardizing the interface for geoprocessing on the Web such as the Web Processing Service (WPS) (Schut, 2007), geoprocessing functionality has been integrated into various applications (Brauner et al., 2009) and the Geoprocessing Web evolved. The Geoprocessing Web makes geoprocessing functionality available on the web, which can be used interchangeably. To ensure interoperability of this functionality, profiles have been proposed to be used in the Geoprocessing Web. A profile consists of unique identifiers for its processes implemented as Unified Resource Names (URN), and of process descriptions including the definition of input and output parameters. An example of a profile related to aggregation is described by Foerster (2010) in the context of generalization. Related to processing of observations, Chen et al. (2010) describe a standards based processing system for wildfire detection in a Sensor Web environment. The use of standardized geoprocessing in wildfire analysis, smoke data analysis, and forecast has also been described and evaluated by Falke et al. (2008). As a possibility for a web-based aggregation, Pebesma et al. (2011) introduce a web service for the automated spatial interpolation of observations. However, the service does not provide spatio-temporal interpolation methods.

When processing sensor data in the Web, provenance information is crucial to determine the quality of the information derived. Recently, several initiatives have developed models for providing provenance information in the Web. The Open Provenance Model (OPM)[1] defines a model for provenance graphs enabling to retrace an information item in the Web back to its origin. Similarly, a Provenance Vocabulary has been defined that can be used, for example, in Linked Open Data (Hartig and Zhao, 2010). Related to sensors, Liu et al. (2010) propose a provenance-aware virtual sensor using the OPM. The virtual sensor provides continuous observations estimated from values gathered by surrounding physical sensors. We are also conceptualizing the aggregation process as a virtual sensor, but rather in the sense of a software sensor like described by Kabadayi et al. (2006) to integrate the aggregation process in our observation data. Instead of adding additional provenance metadata like described by Park and Heidemann (2008), the provenance information is directly provided in our model. Thus, following the final report of the W3C Provenance Incubator Group,[2] our approach is providing provenance information passed by value and embedded in the representations. It allows to retrieve relevant provenance

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[1] http://openprovenance.org/

[2] http://www.w3.org/2005/Incubator/prov/XGR-prov-20101214/