Control and Cybernetics

vol. **35** (2006) No. 1

Using Web Services to enhance Geographic Information Systems

by

Roy Ladner[1], Frederick Petry[1], Elizabeth Warner[1] and Kaylan Gupta[2]

[1]DMAP, Naval Research Laboratory, Stennis Space Center MS, USA

[2]AES, ITT Industries, Alexandria, VA & Naval Research Laboratory Washington DC, USA

Abstract: In this paper we describe an approach to the extension of geographic information systems to take advantage of the continuing development of capabilities of the Semantic Web. This is presented in the context of a portal based Geospatial Information Database (GIDB™), an object-oriented spatial database capable of storing multiple data types from multiple sources. We have developed our approach for a specific domain, spatially oriented, meteorological and oceanographic, but this can clearly be applied to other spatial data domains. Finally we illustrate the use of the ontology development system based on Generative Sublanguage Ontologies (GSO), a type of linguistic ontology inspired by the Generative Lexicon Theory, to develop effective domain ontologies.

Keywords: ontology, Web Services, spatial data, GIS.

1. Introduction

Traditionally, analyses based on Geographic Information Systems (GIS) have mostly accessed their own local data store or spatial database. As the Internet has evolved, much more relevant data is available and must be taken into account in GIS decision-making. The further development of the Semantic Web and Web Services technology offers the capability of effectively and efficiently discovering and accessing data. GIS technology must be extended to take advantage of these new web-oriented capabilities such as described in the Geography Mark-Up Language: GML (Lake, Burggraf, Trninic and Rae, 2004). In this paper we shall discuss an object-oriented geographic data portal that incorporates Web Services capabilities. Our specific application context is that of spatially oriented meteorological and oceanographic (MetOc) data, but the approach should be applicable to any form of spatial data. The web-based extension of the system is implemented by a specialized web broker utilizing ontologies for MetOc data. Finally, a brief discussion of the potential use of fuzzy set based ontological representations is given.

Timely provision of spatially based MetOc data is essential in diverse areas such as emergency planning for severe storms, fishing fleet co-ordination, most military operations etc. For example, the D-Day landings in Normandy were critically affected by weather with the massive operation once being postponed 24 hours based on meteorological forecasts. The need for information on weather and sea conditions is just as relevant today. In order to plan an amphibious beach landing a Special Operations unit must know about the possible sea state conditions to decide the type of craft they can operate effectively. Thus, there is a need to access appropriate MetOc data and forecasts for an operational area that is shared throughout the planning process.

Data integration is a pervasive issue in many areas such as data warehouses and federated/distributed databases (Elmasri, Navathe, 2004). GIS access to and retrieval of data from heterogeneous sources in a distributed system such as the Internet also poses many difficulties. Assimilation of spatio-temporal data from Web-based sources means that differences in notation, terminology, usage, etc. prevent simple querying and retrieval of data. These factors have been extensively explored before the Web for the process of conflation of spatial data in which maps are merged to yield higher quality, more accurate products (Chung et al., 1998; Rahimi et al., 2002).

The recognition of such integration difficulties has influenced many of the concepts that are embodied in the Semantic Web. Ontology tools have been developed to support the goal of sharing knowledge for various domains of interest. Currently, the development of ontologies for geosciences data has been limited. This has restricted the usage of the full potential of the Semantic Web in the area of GIS (Reitsma, Albrecht, 2005).

2. Geographic information systems and data servers

Geographic information systems have become a major tool in a multitude of areas for both commercial and governmental purposes worldwide. A key aspect of a GIS is the underlying spatial database that supplies the volumes of various types of data needed for the variety of applications that have motivated their usage. There are two main types of spatial data in these databases, vector and raster. Vector geographic features use geometric primitives such as points, lines, curves, and polygons to represent map features such as roads, rivers, political boundaries, etc. Raster geographic data types are generally structures that consist of arrays of pixels with given values. This can include scanned maps and charts, and airborne, satellite, and sonar imagery, among others (Sample, McCreedy, 2005).

Although in many applications the data required is already present in the spatial database, it is becoming more common that some of the data will be obtained from the Internet. Our main concern here is how spatial data can be obtained over the web and the types of geographic data servers used to access the data. Geographic data servers can be quite varied. Some are built on robust database management systems (DBMS). Others are simply data transport mechanisms for sensor data or other observations.

The most basic types of geographic data servers can be as simple as a web page or FTP (File Transport Protocol) site with geographic data files available. For example, public and private weather services provide imagery and forecasts on the websites in the form of pre-rendered maps. Another class of servers are more comprehensive software systems that provide a user with a complete, often specialized, map view. These are usually expensive and advanced server systems, which include a DBMS, fully functional geographic information system (GIS), and some type of map renderer. Many of these systems require users to use a specific client software package to access the server. Several vendors currently provide these types of software; examples are ESRI's ArcIMS and AutoDesk's MapGuide. Interfaces to these types of servers vary and can be troublesome to integrate and typically involve a mixture of open and closed proprietary protocols. A more general approach using an open-source object-oriented database is described in the next section

3. GIDB™ – an object-oriented database

The Digital Mapping, Charting and Geodesy Analysis Program (DMAP) at the Naval Research Laboratory has been actively involved in the development of a digital geospatial mapping and analysis system since 1994 (Cobb et al., 1998; Needham, Wilson and Show, 2001). The core of the system is the Geospatial Information Database (GIDB™), an object-oriented spatial database capable of storing multiple data types from multiple sources.

The GIDB includes an object-oriented data model, an object-oriented database management system (OODBMS) and various analysis tools. While the model provides the design of classes and hierarchies, the OODBMS provides an effective means of control and management of objects on disk such as locking, transaction control, etc. The database component of the system is now implemented in an open source, all-Java, object-oriented database management system called *Ozone* (2003). Spatial and temporal analysis tools include query interaction, multimedia support and map symbology support. The GIDB offers 3D terrain visualizations with map overlay (Ladner, Abdelguerfi and Shaw, 2000). Users can query the database by area-of-interest, time-of-interest, distance and attribute. For example, statistics and data plots can be generated to reflect wave height for a given span of time at an ocean sensor. Interfaces are implemented to afford compatibility with Arc/Info, Oracle 8i, Matlab, and others.

An object-oriented approach has been beneficial in dealing with complex spatial data, and it has also permitted integration of a variety of raster and vector data products in a common database. The raster data include Next Generation Radar (NEXRAD) and other weather radar and weather satellite output, Compressed ARC Digitized Raster Graphics (CADRG), Controlled Image Base (CIB), jpeg and video. Vector data include Vector Product Format (VPF) products from the National Geospatial Intelligence Agency (NGA), Shape, real-time and in-situ sensor data and Digital Terrain Elevation Data (DTED).

A communications gateway or portal enables users to obtain data from a variety of data providers distributed over the Internet, in addition to the GIDB, including, for example USGS, Digital Earth/NASA, the Geography Network/ESRI and the Fleet Numerical Meteorology and Oceanography Center (FNMOC). This portal establishes a well-defined interface that brings together such heterogeneous data for a common geo-referenced presentation to the user (Wilson et al., 2003). Differences in data formats are resolved to a uniform format and all data is re-projected to a uniform map projection. An illustration of the interface for a typical data request is shown in Fig. 1.

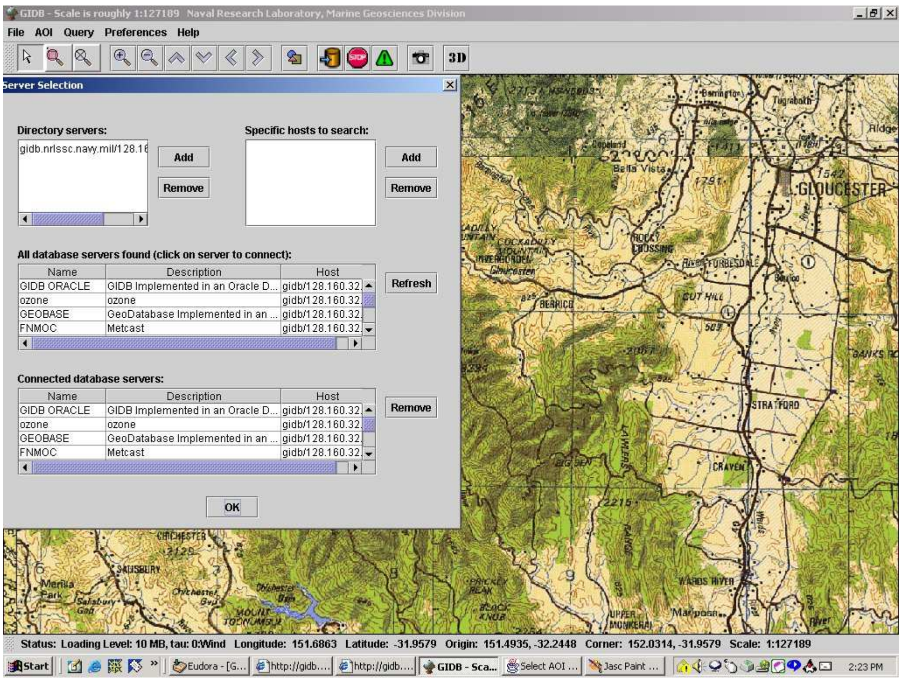


Figure 1. GIDB interface

4. Web Services

In this section we overview some of the technology of Web Services as needed for the description of our web-enhanced GIS system. Web Services provide data and services to users and applications over the Internet. The most commonly used Web Services standards and protocols include, but are not necessarily limited to, the Extensible Markup Language (XML), Simple Object Access Protocol (SOAP), the Web Services Definition Language (WSDL) and the Universal Discovery Description and Integration (UDDI) (Dick, 2000).

XML is a language used to define data in a platform and programming language independent manner. XML has become one of the widely used standards in interoperable exchange of data on the Internet but does not define the semantics of the data it describes. Instead, the semantics of an XML document are defined by the applications that process them.

XML Schemas define the structure or building blocks of an XML document. Some of these structures include the elements and attributes, the hierarchy and number of occurrences of elements, and data types, among others.

WSDL allows the creation of XML documents that define the “contract” for a Web Service. The “contract” details the acceptable requests that will be honored by the Web Service and the types of responses that will be generated (Cerami, 2002). The “contract” also defines the XML messaging mechanism of the service. The messaging mechanism, for example, may be specified as SOAP.

A UDDI registry provides a way for data providers to advertise their Web Services and for consumers to find data providers and desired services. Data provided about a Web Service can be categorized much like information in a telephone book into “white” pages, “yellow” pages and, unlike a telephone book, the “green” pages. The white pages include basic provider information such as name, address, business description and contact information. The yellow pages provide services listed by category as determined by the American Industry Classification System and the Standard Industrial Classification. The white and yellow pages include enough information for a consumer to determine whether they need the technical specification for the service, which is contained in the green pages. The green pages may either contain or point to the WSDL file. An interface to a UDDI registry may allow users to search for Web Services by business category, business name or service.

It is, of course, not necessary to register a Web Service with a UDDI registry. However, that would be similar to a business not listing its telephone number in a telephone directory. Not having a listing would make it more difficult for consumers to discover and utilize a Web Service.

A graphic representation of the Web Services protocol stack as described above is shown in Fig. 2 (Cerami, 2002). A Web Service describes its interface with a WSDL file and may be registered in a UDDI registry. Interfaces defined in XML often identify SOAP as the required XML messaging protocol. SOAP allows for the exchange of information between computers regardless of platform or language.

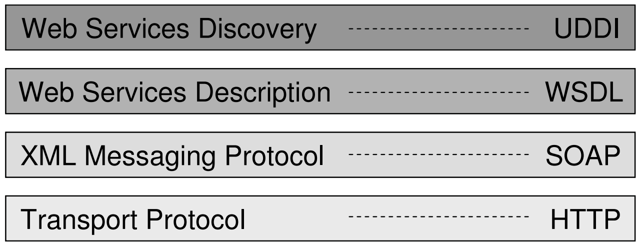


Figure 2. Web Services protocol stack

A sample use of the protocol stack is illustrated in Fig. 3. The Web Service publishes its existence with one or more UDDI registries. Next, a user discovers the service from a UDDI registry and retrieves a description of the service. The user then either automatically invokes the service or writes an application that invokes the service by sending an XML message over the specified transport to the service. The Web Service then returns an XML message over the specified transport.

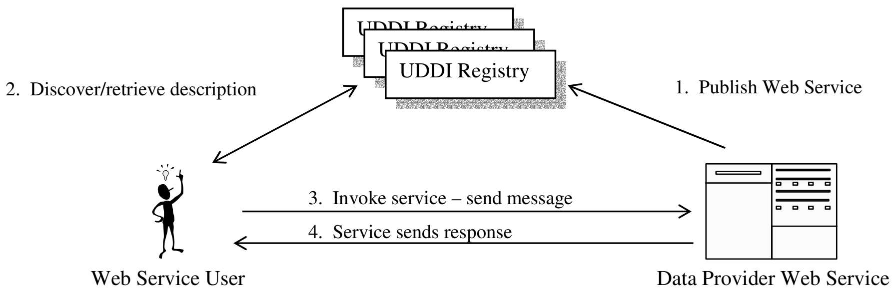


Figure 3. Illustrated use of Web Services

There are applications that provide services on the Web without using all components of the Web Services protocol stack described above. These Web-based services employ diverse methods for discovery, description, messaging and transport. Within these Web-based services adherence to standards and protocols vary.

5. Web Services for MetOc data

Our current concentration in net-centric operations is focused on improving delivery of MetOc data in order to achieve this information superiority for tactical operations planning. Some specific architectures using Web Services and Web-based services for such data are described next in this section.

The Navy Enterprise Portal (NEP) is a Web Service access portal. The NEP provides Web-browser based user interfaces or user-facing services, which interact with data oriented services on remote servers. A data oriented service is not tightly coupled to any client application. The NEP allows the user to simultaneously access multiple user-facing services from the same Web-browser interface (*Navy Enterprise Portal*, 2004).

The Joint MetOc Broker Language (JMBL) is a specification for a standard language to be used in MetOc Web Services to broker the exchange of information between MetOc data providers and user applications. JMBL does not define a data model, but simply a syntax that allows standardized request and response structures for MetOc data queries. A motivating factor in the creation of JMBL was the need to move beyond having distinct interfaces for every possible combination of user application systems and data provider systems. The goal of JMBL was to define one Web Service based on jointly defined XML Schemas that would serve all types of MetOc data requests.

The JMBL Web Service is defined by one WSDL file and several XML Schemas (Warner et al., 2005). These define the structure of requests that the JMBL Web Service will accept and the structure of responses that it will provide. The request and response schemas include several other schemas, which define global data types and structures. Fig. 4 shows this conceptual organization with several of the global schemas included in other global schemas. Schemas in the figure are represented by "XSD".

Even with the advent of Web Services and Web-based services, human resources are still required to integrate these data sources into applications. Compatibility of XML schema versions is an inherent issue, and Web Services based on common XML schemas may be implemented in a manner to create inconsistent results.

GIDB, for example, does not automatically discover new Web Services or Web-based data services. A human in the loop is necessary to find relevant data on the Internet and write application code to connect the GIDB Portal System to the data source. The GIDB currently connects to over 600 servers offering over 2,500 services. The fact that some of the code used to connect to these servers is common to multiple servers helps with code development and maintenance.

While GIDB establishes a single portal to multiple servers, JMBL seeks to establish a uniform Web Service that can be separately implemented by multiple data providers. JMBL seeks to accomplish this through adoption of a specified XML Schema and WSDL. Our experience has been, however, that

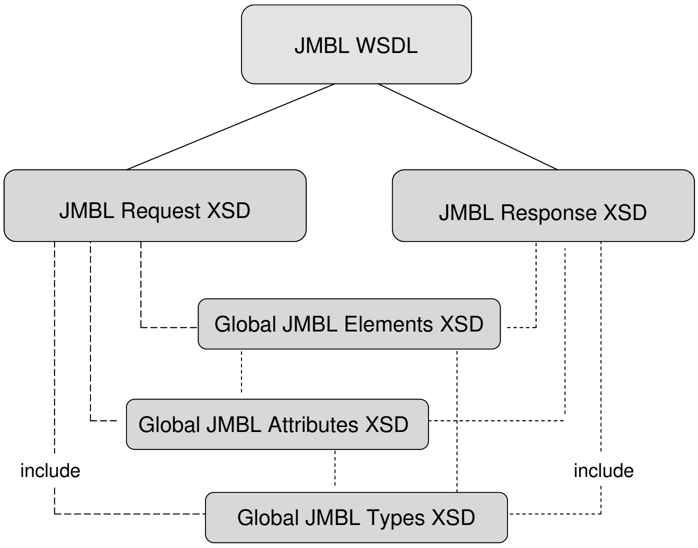


Figure 4. Conceptual view of JMBL WSDL and schemas

the implementation of the Web Service by different data providers can create the likelihood of varying implementations that may impact interoperability. In these cases, client side code that conforms to the particular implementation must be developed. Based on our experience, service providers can choose to implement as much or as little of the JMBL Schema as they wish. The XML Schema, for example, allows users to request data that has been modified since a specified date and time. Because of the variations in implementation of these Web Services, while one service provider supports data responses to this request, another service provider returns an error message. Although both providers produce gridded numerical forecast model output on a scheduled timetable, the provider producing the error message does not believe that any users would request its data in that manner.

A need exists for resolving semantic and business rule differences that result from specific implementations. While, as described above, JMBL defines a syntax that allows standardization of terms used to request MetOc information and respond to such requests, the semantics are not tightly defined. JMBL Web Service implementers are free each to implement a different sub-set of JMBL and each may interpret various JMBL elements and attributes in incompatible ways. Work is underway to produce a set of conventions and JMBL modifications that will reduce this ambiguity.

6. MetOc broker

With Web Service technology playing an ever-increasing role in net-centric operations and new web services becoming available, the need exists for applications to quickly and easily integrate with these web services. As we have discussed, the web services technology has freed developers from platform and programming language constraints, but it has not yet freed developers from writing code that connects to server applications. Web Service technology merely defines the specifications (WSDL and XML Schemas), to which the client application developer must conform. These schemas may be complex and in addition, structural and semantic differences may exist between web services.

Since web services give the promise of discoverable, self-describing services that conform to common standards, their use should allow the possibility of an efficient and automated capability to obtain and integrate data (Cerami, 2002). Ideally, with this automated capability it should be possible to obtain and integrate data (1) from alternate sources when data becomes unavailable from a previously reliable source, (2) from newly identified data sources that possibly employ previously unseen schemas or (3) from a known source that changes its interface definition.

Our approach to these problems was the development of an Advanced MetOc Broker (AMB), which supports the automated identification, retrieval, and fusion of MetOc data from new and ad hoc web services. Our approach to automating the AMB's recognition of terms used by new web services for data requests and responses is to apply MetOc ontologies to meteorological and oceanographic forms of data (Fonseca, Davis 1999; Fonseca and Davis, 2002; Alameh, 2003). Since the MetOc domain is well understood, this process can overcome many semantic limitations inherent to MetOc web services. The AMB uses a mapping function to resolve semantic differences and integrate data. The description of concepts and terms inherent in MetOc ontologies provide the resolution of different schemas that may have varying semantics but describe similar data requests and responses.

Fig. 5 shows an example of a high level conceptual description of the mapping process, in which ontology usage may enable an automated mapping process. A data provider uses the term "temp" and the AMB uses the term "air_temperature". These need to be mapped as equivalent. This is shown in the mapping with source term "temp" mapping to "temperature". The CONCEPT_AIR in the ontology (mapping dictionary) is used to resolve this mapping. Therefore MetOc Web Services using domain-relevant terminology are discoverable by the AMB and the AMB can resolve requests to and responses from these new web services.

Although our focus is on the MetOc domain, the methodology employed by the AMB is extendable to other spatial domains. Systems based on this approach would not require extensive client application development for each new web service from which data can be retrieved. Similarly, extensive client

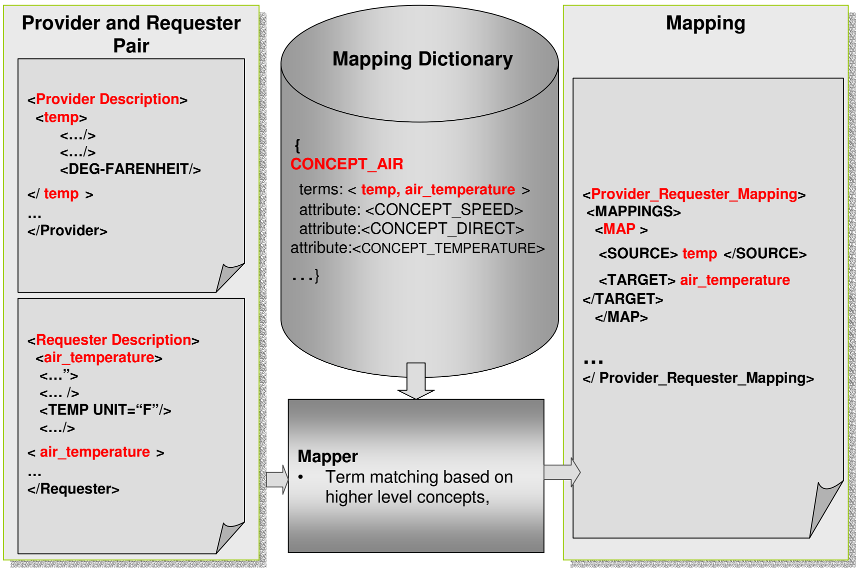


Figure 5. Conceptual view of ontology mapping process

application maintenance would not be required for each schema alteration that may be made to the schemas of existing web services.

7. Ontology development for MetOc data

The development of the ontology structure for the AMB has involved the elicitation of concepts, terms, etc. from multiple sources. An example in Fig. 6 focuses on oceanographic data that have been the basis of our initial development due to the availability of resources and experts and its somewhat simpler structure. We have used access to resident oceanographic data experts at the Naval Research Laboratory to provide an initial organization of oceanographic concepts. Additionally, since we obtain data from various web sources whose terminology must be reflected in the ontologies, we have included in structure of Fig. 6 descriptions of the sources and models that produce some of the data.

In Fig. 7 we show the relationship between the terms in the ontology index on the left of the figure and the web services that may be accessed for the terms. So the MetOc broker queries using terms as follows: The terms from the input request will be used to create a query (e.g. getdata, sal etc.) and the query term (e.g. sal or salinity) will be used to retrieve concepts using the term concept index. The concept will then serve as the key to web service

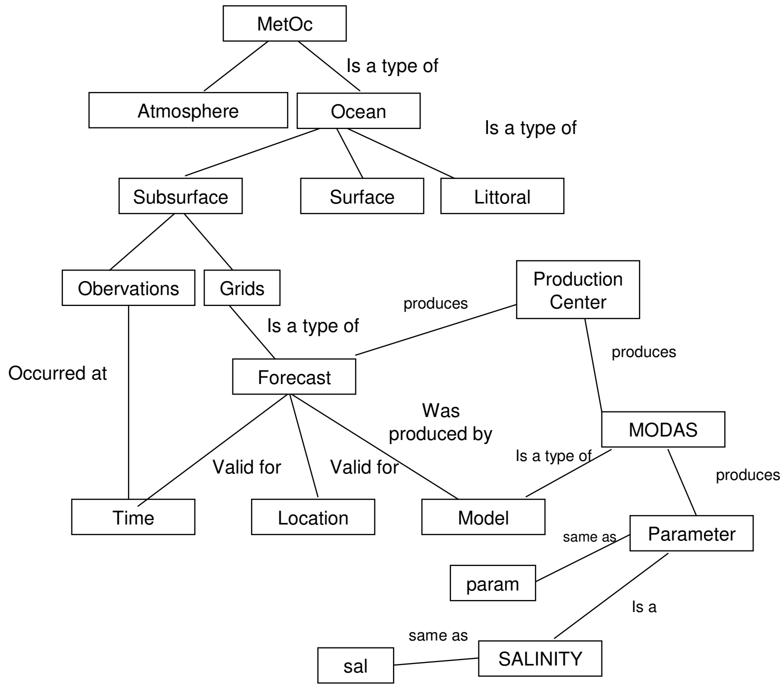


Figure 6. Sample concepts/terms and their relationships

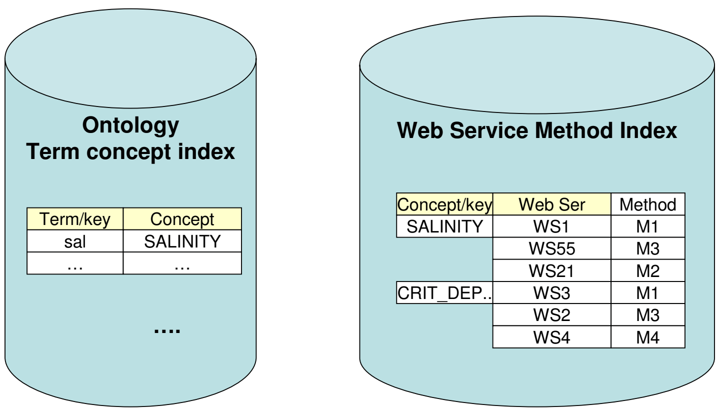


Figure 7. Ontology and Web Services indexes

method index from which the appropriate web services and their methods will be retrieved. If more than one web service and method are retrieved we are evaluating selection/filter algorithms to rank (e.g., by confidence) select among them. The ranking will reflect measures of confidence of the data's availability, reliability and suitability. This may include confidence parameters that reflect the data source's current availability, the status of the source (e.g., government, military, educational, foreign, etc.) and the timeliness of the data. Once the candidate web service and their methods are retrieved, the input request will need to be translated to the request format of the identified web service.

8. GSO System

The ontology development system we used for the AMB is based on Generative Sublanguage Ontologies (GSO), a type of linguistic ontology inspired by the Generative Lexicon Theory (Gupta, Aha, 2003, 2005). These approaches provide a compact conceptual representation of related word meanings that can be used to robustly and accurately interpret natural language sentences. They also provide generative operators that can be used to select the correct meaning of a word from the possible alternatives for a given context. Their robustness arises from the ability to use these operators for situations where the words are used in creative and unanticipated ways.

GSOs are one of the first implementations of the Generative Lexicon Theory and have the following architecture implemented in Java (see Fig. 8). The *GSO Editor* is a graphical user interface that can be used to add, edit, and modify the ontology for a selected application domain such as AMB. It provides a

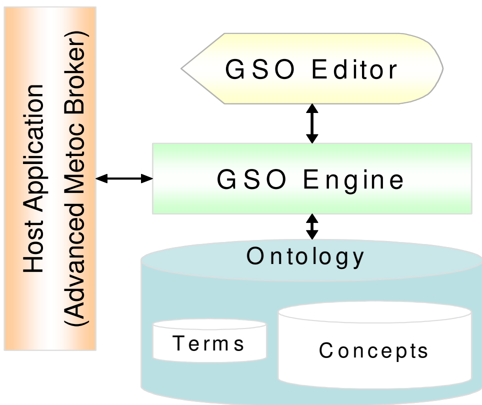


Figure 8. GSO system architecture

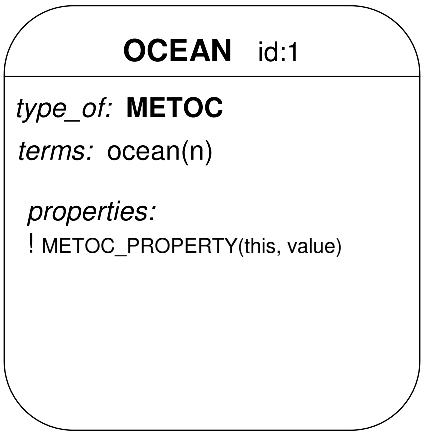
user-friendly drag and drop interface and performs knowledge integrity checks during editing. For example, it prevents the user from specifying cyclic inheritance relations and prevents the user from deleting concepts that are used in the representation of others. It relieves the user of performing several representation consistency and completeness checks. These checks are performed by the *GSO Engine* among its other functions. Host applications such as AMB access the application specific ontology via the GSO Engine interface, which is capable of responding to various queries from the host. For example, in AMB, the following query could be issued by AMB: "Get all concepts pertaining to the term *salinity*". The GSO engine would return the corresponding GSO concept SALINITY, which states that it is a property of water and in particular seawater. In addition, the GSO Engine also provides various functions to compute synonymy and similarity computation across concepts that can be used for partial mapping. The ontology comprises two main components: the terms and the concepts that they point to. The concepts are represented using the GSO representation approach, which is a first order predicate calculus representation embedded in an object-oriented framework (Gupta, Aha, 2003).

This is illustrated by the oceanographic data design components in Figs. 9 and 10. The high level concept Ocean is first shown followed by the subconcepts, Surface and Subsurface. Next two properties, Salinity and Depth are illustrated.

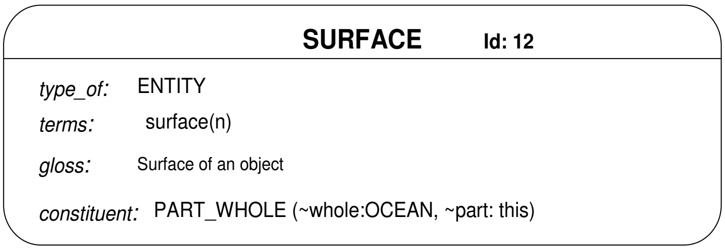
Concepts are shown in a rounded box with the name of the concept at the head of the box. Slot names are italicized and are in lower case. Two reserved symbols are "this" referring to the concept itself, and "!", a GSO symbol showing that a slot is inherited from one of the ancestors. Arguments are referred by the aliases indicated by a tilde "∼", like a variable name in an object. Terms are lower case non-italicized, comprising one or more words and or symbols. Terms have an associated part of speech such as (v) indicating a verb, (n) - noun, (a) - adjective, etc.

9. Fuzzy ontology extensions

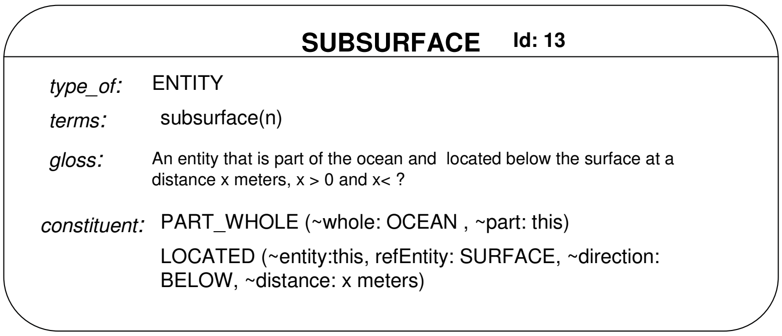
In the ontology approach we have described above, matching of differing terms is based on syntactic variations and/or the relationships implicit in the ontology's conceptual structure. However, a valuable extension would be to consider the capability for approximate matching that captures in some fashion a degree of matching. This may be desirable to be taken into account to provide weighted overall matches on discovery of data sources. Related issues have previously arisen in the hierarchical structures that are used in both fuzzy object-oriented databases (George, Srikanth, Buckles and Petry, 1997), and in the conceptual hierarchies for association rule (Chen, Wei and Kerre, 2000; Lake, Burggraf, Trninic and Rae, 2003) and attribute-oriented generalization data mining approaches (Angryk and Petry, 2003). In these the relationship among terms can differ in the database querying aspect or in the data mining applications in



(a) Ocean structure



(b) Surface structure



(c) Subsurface structure

Figure 9. Ontology diagrams

SALINITY **Id: 29**

type_of: PROPERTY, PARAMETER

terms: salinity(n), sal(n)

gloss: Salinity of sea water

Argument Alias	Argument Type
~object	SEAWATER
~level	MEASURED_VALUE

Behavior: !METHOD(~returnedObject:?, this)

(a) Salinity structure

Id: 30 **DEPTH**

type_of: PROPERTY, PARAMETER

terms: depth(a), depth(n)

gloss: Depth at which the observations are made

Argument Structure:

Argument Alias	Argument Type
~entity	ENTITY
~entity'sTop	TOP(~entity)
~depthLoc	ENTITY or BOTTOM(~entity)
~deep	VALUE/NUMBER

Behaviour(s): LOCATED(~object: ~depthLoc, ~refObject: ~entity'sTop, ~direction: BELOW, ~distance: ~deep)

!METHOD(~returnedObject:?, this)

(b) Depth structure

Figure 10. Ontology diagrams

which terms in the data warehouse are not exact matches to the given hierarchical structure. In such cases the use of measures such as fuzzy similarity or proximity relationships among the terms has proven fruitful.

Currently, there are specific efforts to apply fuzzy ontologies to web searching in the context of document retrieval (Widyantoro, Yen, 2001; Parry, 2004). Such ontologies are typically based on a corpus of documents, abstracts or citations. This corpus is then analyzed to generate the fuzzy ontology based on analyses of frequencies of term occurrences/co-occurrences.

In the environment of Web Services a similar approach can be taken to exploring UDDI registries for appropriate Web Services and to basing term analyses on these as described above. However, since we are also often focused on a specific domain, as in our application for MetOc data, then it is to be expected that there must also be a part of the ontology based on this specific domain's structure. Typically, elicitation from experts/expert sources is utilized for this, and we can expect issues of term similarity that arise from such multiple sources to be able to be captured in a fuzzy ontology structure. Finally, various domain ontologies for many specific areas are rapidly being developed around the world. To make use of such pre-existing ontologies, we believe will require their merging/ intersection. This merging would also be facilitated by a fuzzy ontology in order to support term differences that occur across the various ontologies. Indeed, current research that is underway indicates that this is a feasible goal (Taylor, Poliakov and Mazlack, 2005).

10. Conclusions

This paper has illustrated an approach to the extension of geographic information systems to take advantage of the continuing development of capabilities of the Semantic Web. We have shown this in the context of a specific domain, MetOc data, but clearly this approach can be applied to other spatial data domains. Most important for this extension is the ability to develop effective domain ontologies. Extensive work is under way in all application areas to develop broadly encompassing ontologies including that of geographic data (Kuhn, 2001; Klein, Einspanier, Lutz and Hubner, 2004; Peachavanish and Karimi, 2004). It is clearly extremely important to extend the capabilities of GIS to take advantage of the Semantic Web and our approach illustrates one such possible extension

Acknowledgements

The authors would like to thank the Naval Research Laboratory's Base Program, Program Element No. 0602435N for sponsoring this research.

References

ALAMEH, N. (2003) Chaining geographic information web services. *IEEE Internet Computing* **12**, 22-29.

ANGRYK, R. and PETRY, F. (2003) Consistent Fuzzy Concept Hierarchies for Attribute Generalization. *Proc. IASTED Int.Conf on Information and Know-ledge Sharing*, Scottsdale AZ, 158-163.

CHUNG, M., COBB, M., FOLEY, H., PETRY, F. and SHAW, K. (1998) A Rule-based Approach for the Conflation of Attributed Vector Data. *GeoInformatica* **2**(1), 1-29.

CHEN, G., WEI, Q. and KERRE, E. (2000) Fuzzy data mining: discovery of fuzzy generalized association rules. In: G. Bordogna and G. Pasi, eds., *Recent Issues on FuzzyDatabases.* Physica-Verlag, Heidelberg, 45-66.

CERAMI, E. (2002) *Web Services Essentials*. O'Reilly and Associates, Sebastopol, CA.

COBB, M., FOLEY, H., WILSON, R., CHUNG, M. and SHAW K. (1998) An OO Database Migrates to the Web. *IEEE Software* **15**, 22-30.

DICK, K. (2000) *XML: A Manager's Guide*. Addison Wesley, Reading MA.

ELMASRI, R. and NAVATHE S. (2004) *Fundamentals of Database Systems*, 4^{th} ed. Addison Wesley.

FONSECA, F. and DAVIS, C. (1999) *Using the internet to access geographic information in Interoperating GIS*. Kluwer Academic Publishers, Norwell MA.

FONSECA, F., EGENHOFER, M., AGOURIS, P. and CAMARA, G. (2002) Using ontologies for Integrated geographic information systems. *Transactions in GIS* **6** (3), 47-61.

GUPTA, K. and AHA, D. (2003) Nominal Concept Representation in Sublanguage Ontologies. In: P. Bouillion and K. Kanzaki, eds., *Proc. 2nd Int. Workshop on Generative Approaches to the Lexicon*, Geneva, Switzerland: School of Interpretation and Translation, University of Geneva, 53-62.

GUPTA, K. and AHA, D. (2005) Interpreting Events using Sublanguage Ontologies. In: P. Bouillion & K. Kanzaki, eds., *3^{rd} Int. Workshop on Generative Approaches to the Lexicon*, Geneva, Switzerland: School of Interpretation and Translation, University of Geneva, 78-85.

GEORGE, R., SRIKANTH, R., BUCKLES, B. and PETRY, F. (1997) An Approach to Modeling Imprecisness and Uncertainty in the Object-Oriented Model. In: D. Dubois, H. Prade, R. Yager, eds., *Fuzzy Set Methods in Information Engineering: A Guided Tour of Applications*, Wiley Press NY, NY, 73-84.

KLEIN, E., EINSPANIER, U., LUTZ, M. and HUBNER, S. (2004) An Architecture for Ontology based Discovery and Retrieval of Geographic Information, *Proc. 7^{th} Conf. on Geographic Information Science*, AGILE 2004, 179-188.

KUHN, W. (2001) Ontologies in Support of Activities in Geographical Space, *IJGIS* **15** (7), 613-631.

LADNER, R., ABDELGUERFI M. and SHAW K. (2000) 3D Mapping of an Interactive Synthetic Environment. *IEEE Computer* **33** (3), 35-39.

LADNER, R., PETRY, F. and COBB, M. (2003) Fuzzy Set Approaches to Spatial Data Mining of Association Rules. *Transactions in GIS* **7** (1), 123-138.

LAKE, R., BURGGRAF, D., TRNINIC, M. and RAE, L. (2004) *GML Geography Mark-Up Language*. J. Wiley, Chicester, UK.

Navy Enterprise Portal (2004) https://portal.tfw.navy.mil, http://agendas.ca.com/agendas/SessionDetails.asp?SessionId=1595, http://ams.confex.com/ams /Annual2005/techprogram/paper_86973.htm

NEEDHAM, D., WILSON, R. and SHAW, K. (2001) An Analysis of a CORBA-based Approach to Accessing Geospatial Information via the Internet. *Proc. 20th IEEE Int. Performance, Computing, and Communications Conf. (IPCCC 2001)*, April 4-6, 236-243.

Ozone, (2003)http://www.ozone-db.org.

PARRY, D. (2004) A Fuzzy Ontology for Medical Document Retrieval. *Proc. Australian Workshop on Data Mining and Web Intelligence*, 210-215.

PEACHAVANISH, R. and KARIMI, H. (2004) GeoInterpert: Ontological Engineering Framework for Geospatial Query Analysis. *Proc. GIScience 2004*, Aldephi, MD, 168-172.

RAHIMI, S., COBB, M., DIA, A., PAYRICK, M. and PETRY, F. (2002) A Know-ledge-Based Multi-Agent System for Geospatial Data Conflation. *Journal of Geographic Information and Decision Analysis* **2** (5), 67-81.

REITSMA, F. and ALBRECHT J. (2005) Modeling with the Semantic Web in the Geosciences. *IEEE Intelligent Systems*, 86-88.

SAMPLE, J. and MCCREEDY, F. (2005) Distributed Geospatial Intelligence Integration and interoperability through the GIDB® Portal System. In: R. Ladner and F.Petry, eds., *Net-Centric Approaches to Intelligence and National Security*, Kluwer Press, 55-82.

TAYLOR, J., POLIAKOV, D. and MAZLACK, L. (2005) Domain-specific Ontology Merging for the Semantic Web. *Proc. NAFIPS 2005* (CD), Ann Arbor MI.

WARNER, E., KATIKANENI, U., LADNER, R., PETRY, F. and SHAW, K. (2005) Web Services Overview for Net-Centric Operations. In: R. Ladner and F.Petry, eds., *Net-Centric Approaches to Intelligence and National Security*, Kluwer Press, 13-27.

WILSON, R., COBB, M., MCCREEDY, F., LADNER, R., OLIVIER, D., LOVITT, T., SHAW, K., PETRY, F. and ABDELGUERFI, M. (2003) Geographical Data Interchange Using XML-Enabled Technology within the GIDB System, Chapter 13. In: A.B. Chaudhri, ed., *XML Data Management*, Addison-Wesley, 353-374.

WIDYANTORO, D. and YEN, J. (2001) Using Fuzzy Ontology for Query Refinement in a Personalized Abstract Search Engine. *Proc. IFSA World Congress* (CD), Vancouver Canada.