A REAL TIME SEMANTIC INTEROPERABILITY FRAMEWORK FOR AD HOC NETWORK OF GEOSPATIAL DATABASES: DISASTER MANAGEMENT CONTEXT

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ABSTRACT:

Disasters are events that cross geographical, organisational and other human-made or natural boundaries. Therefore, disaster management requires that various geospatial data producers and users collaborate together in an ad hoc manner, despites their different background and contexts. While semantic interoperability is meant to support meaningful communication between geospatial databases, semantic interoperability approaches that were designed for static and closed environments, or that do not address the particularities of geospatial data, are not suitable for supporting disaster management. In this paper, we describe a new approach for supporting real time semantic interoperability in ad hoc network of geospatial databases that can answer the needs of disaster management. The major components of our framework include (1) the discovering and formation of meaningful coalitions of geospatial databases which integrates quality of data sources' descriptions (metadata) to improve discovering results; (2) a tool for semantic extraction based on a new concept representation, called the Multi-View Augmented Concept; (3) the semantic reconciliation of heterogeneous geospatial databases through semantic mapping process in static network ; (4) multi-strategies query propagation method to account for changes in the ad hoc network. Finally, we demonstrate how this framework can contribute to support disaster management.

1. INTRODUCTION

When cities of larger urban areas are stricken by natural of human disasters, the emergency teams responsible for disaster response, rescue and relief are overloaded and need to maximize all available resources. Information about the damages and resources, and their geographical location is essential to support the operations. Therefore, an efficient and integrated system could support the operations and help reducing the damages and casualties (Markus et al. 2004).

The emergency response cycle includes four main phases: following the event, it begins with the rescue and relief operations, which are followed by recovery, the reconstruction, and the preparation in case of new disaster (Cutter 2003). All those phases require geospatial data to make appropriate decisions (Goodchild 2006). In disaster management, decisions must be founded on a comprehensive picture of the situation; they must also be made rapidly. Decision makers require data that come from different sources in order to corroborate uncertain information; the risk of misinterpreting data must be minimal in order to reduce wrong decisions (Bakillah et al. 2007).

Data integration and interoperability were identified as major challenges of Geographical Information (GI) Science in disaster and emergency management (Cutter 2003). In the geospatial domain, a well-known definition of interoperability is given in ISO TC204, document N271: interoperability is *"the ability of systems to provide services to and accept services from other systems and to use the services so exchanged to enable them to operate effectively together."* Semantic interoperability is also defined for systems as the knowledge-level interoperability that provides cooperating databases with the ability to resolve semantic heterogeneities arising from differences in the meaning and representation of concepts (Park and Ram 2004). It is also the analogous to communication and cooperation between humans (Brodeur et al. 2003; Kuhn 2005). Several semantic interoperability frameworks have been proposed in recent years, both in the geospatial domain (Bishr 1998; Brodeur et al. 2003; Rodriguez and Egenhofer 2003; Ahlqvist 2005; Kuhn 2003; Lutz et al. 2003; Kavouras et al. 2005; Lutz and Klien 2006; Bian and Hu 2007; Hess et al. 2007; Cruz and Sunna 2008; Schwering 2008; Staub et al. 2008; Bakillah et al. 2009b; Vaccari et al. 2009; Hossein et al. 2010; Zhang et al. 2010) and in the larger information system community (Kalfoglou and Schorlemmer 2003; Park and Ram 2004; Cudré-Mauroux 2006; Keeney et al. 2006; Euzenat and Shvaiko 2007). In ad hoc networks, the databases that have to interoperate are not known in advance (Lutz et al. 2003). Traditional semantic interoperability systems that were dedicated to a limited number of known sources are no longer appropriate for the new distributed and heterogeneous environments, such as ad hoc networks, due to their thigh coupling and their lack of flexibility (Tsou and Buttenfield 2002). However, existing semantic interoperability frameworks that were dedicated to dynamic environment such as peer-to-peer networks (Cudré-Mauroux 2006; Montanelli et Castano 2008) and distributed databases (Park and Ram 2004) as well as numerous automatic or semi-automatic semantic mapping approaches use knowledge representations that are not rich enough to represent geospatial concepts. On the other hand, frameworks for interoperability of GIS do not integrate capacities to deal with dynamicity of networks, that is, dynamic

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matching at run-time, and using different strategies when requirements are changing. The objective of this paper is to propose an architecture for real time semantic interoperability that integrate both requirements of the geospatial domain and of dynamic, ad hoc networks and, gives high value to deep semantics representation. This architecture's major components deal with establishing coalitions of geospatial databases to support geocollaboration, enriching the semantics of geospatial concepts, automating a semantic mapping process that is suitable for geospatial concepts and propagating geospatial queries to relevant nodes of the network with different strategies. With a prototype implementation and scenario, we aim at demonstrating that the proposed approach is useful for supporting disaster management tasks.

2. RELATED WORK

Semantic interoperability is a requirement for the meaningful sharing of geospatial data. Semantic interoperability is mainly hampered by heterogeneity, which can be syntactic, structural and semantic (Brodeur et al. 2003). The latter refers to differences in the meaning of concepts. For example, *geometry of building* may represent the *roof of the building* or the *foundation of the building*. Resolution of semantic heterogeneity is not the only concern that must be address to achieve semantic interoperability: in ad hoc networks, the members that can collaborate and exchange data also have to be discovered. Previous semantic interoperability frameworks, for example the Ontology-driven Geographic Information System (ODGIS) of Fonseca et al. (2002), where each ontology is a component that describes the view of a given geospatial information community (GIC), is suitable for a limited number of sources. Several other approaches for the geospatial domain are using ontologies to describe semantics of data or services (Mostafavi et al. 2004; Lutz and Klien 2006; Hess et al. 2007; Cruz and Sunna 2008; Vaccari et al. 2009; Zhang et al. 2010). However, ontologies alone are not the complete solution, since they are themselves semantically heterogeneous. Semantic mapping, which consists in discovering semantic relationships between concepts describing the semantics of data (Kafoglou and Schorlemmer 2003; Euzenat and Shvaiko 2007), is a plausible solution to the semantic heterogeneity problem (Vaccari et al. 2009). However, a major limitation of the semantic mapping approaches is that the quality of its results depends on the quality of its input, or more precisely, on the quality of the representation of semantics (Bakillah et al. 2009a). Implicit knowledge refrains from discovering differences in meaning and conflicts. To detect such differences, a knowledge representation that makes explicit all aspects of geospatial concepts, especially about spatiotemporal features and contexts, is required. Most of the existing semantic mapping frameworks, approaches and tools (several that were presented in the reviews of Kalfoglou and Schorlemmer 2003 and Euzenat and Shvaiko 2007) combine diverse techniques, including string-based and linguistic matching, structural matching based on the taxonomic relations between concepts of the ontology, and use of external resources such as lexicon. In addition, semantic interoperability frameworks for the geospatial domain now start to integrate reasoning capabilities provided by Semantic Web techniques to automate the process (Zhang et al. 2010). Most existing approaches are nevertheless tailored to more simple representation of concepts, where spatiotemporal features are not treated or treated as any other features, contexts are not defined, and structure of the concept is poor. Rather, emphasis is put on reducing the cost of the semantic mapping process and making it automatic. While those are certainly important issues, in the geospatial domain, it does not resolve important heterogeneities.

The issue of finding sources that can answer a given query in decentralized networks has recently been investigated in query propagation approaches that were mainly targeted at peer-to-peer networks (Zhuge et al. 2004; Mandreoli et al. 2006; Montanelli and Castano 2008). In those approaches, the goal is to find the path along which a query issued by a peer can be forwarded to reach only the most relevant peers. Those approaches rely on existing semantic mappings between ontologies of peers (Mandreoli et al. 2006) or semantic mappings that are computed at run-time (Zhuge et al. 2004; Montanelli and Castano 2008) to select the query recipient. In our framework, we propose a different multi-strategy approach were semantic mappings between concepts are not employed at that stage but rather the computed propagation path (graph) will also be useful to determine which geospatial databases of the ad hoc network have to be reconciled. Therefore, the advantage is to reduce the volume of semantic mappings that must be computed.

3. REQUIREMENTS RELATED TO DISASTER MANAGEMENT

In comparison to static and more predictable situations, the tasks related to disaster management impose more constraints on semantic interoperability processes (Goodchild 2006), including the processes of discovering relevant geospatial databases, establishing efficient collaborations, extracting semantics of geospatial data, ensuring the semantic reconciliation of geospatial data, and propagating geospatial queries to relevant geospatial databases. Table 1 provides some example of tasks that may take place during the different phases of disaster management cycle.

Disaster management phase	Task example
Response	Coordinate the allocation of rescue personnel; localise logistical support and resources
Recovery	Produce maps of damages to infrastructures
Reconstruction	Monitor land use; Identify building characteristics and occupancy
Preparation	Produce risk maps; Determine potential evacuation plans

Table 1. Example of tasks related to disaster management

In particular, we have identified the characteristics that should guide the development of a semantic interoperability approach suitable for disaster management:

-The organisms that must collaborate and exchange geospatial data are not known in advance; no common agreement on knowledge representation can be assumed, and semantic heterogeneity is high between their geospatial databases;
-Actors of disaster management must be able to form collaborative groups for short-lived needs;
-Actors of disaster management must obtain fast, up-to-date, but accurate response to their queries;

-To ensure effective communication, conflicts on the meaning of exchanged data must be detected and resolve rapidly;

-Actors of disaster management must access static data (ex: information on building occupancy, demographic data) and dynamic, operational data (water levels, damage detection, meteorological conditions).

In the following, we propose an architecture of a real time semantic interoperability approach that attempt to answer the above requirements and limitations that are highlighted in related work.

4. ARCHITECTURE FOR REAL TIME SEMANTIC INTEROPERABILITY IN AD HOC NETWORKS OF GEOSPATIAL DATABASES

We propose our conception of an architecture that comprises the components estimated to be required to achieve real time semantic interoperability in ad hoc network of geospatial databases.

An ad hoc network is an open network were nodes (often representing wireless devices, mobiles, geospatial databases…) can move freely, enter or quit the network (Hafsia 2001). The ad hoc network is often representing an informal network, where there is no central authority, and each node is autonomous in term of knowledge representation, and processing capabilities. Figure 1 illustrates the proposed architecture.
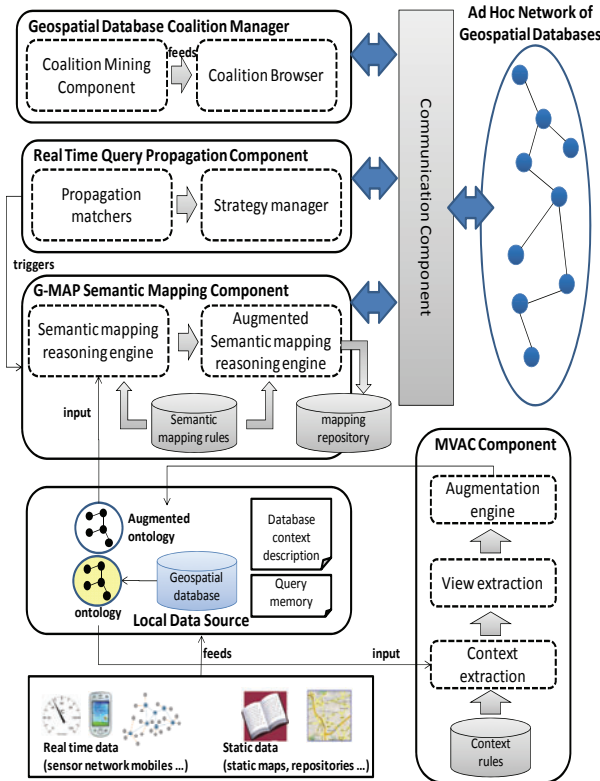

Figure 1. Architecture for real time semantic interoperability in ad hoc networks of geospatial databases

Each node holds a geospatial database which is semantically described by an ontology. The ontology is assumed to be expressed in the standard Ontology Web Language OWL-DL, the standard language for Geospatial Semantic Web applications (Zhang et al. 2010). In addition, nodes hold two more sources of information that are used during semantic interoperability processes:

- Each geospatial database is associated to an OWL description of the context of this database. The context is defined by (1) the geographical location covered by the entities stored in the database, (2) the period of time covered by those same entities, (3) the domain described by the database (ex: roads, water bodies, demography, etc.), (4) the role of the database (ex: monitor water levels, characterize buildings, localise fire hazards, etc.). The purpose of the context description is twofold: for formation of coalition of geospatial databases having similar contexts, and for propagation of geospatial queries.

-Each node holds a list of queries he had previously answered. This list is called the memory of the node. It will be useful for propagation of geospatial queries as well.

A node has four additional components: the geospatial database coalition management component, the MVAC component for semantic extraction and inference, the semantic mapping component, and the query propagation component.

Geospatial database coalition management component. This component is responsible for supporting the discovery of groups of nodes that may collaborate together toward a common goal. Those groups are called *coalition of geospatial databases*. The discovering of coalition is supported by a coalition mining component that uses network analysis techniques to find nodes that may act as central attractor for other nodes. For example, a node may be an attractor node when its interest subsumes all interests of several other nodes. The interest of a node is defined in terms of geospatial location, period of time, domains and roles that may differ from their context descriptions. This coalition mining algorithm resolves granularity conflict between description of interests and contexts. This coalition mining algorithm is detailed in Bakillah et al. (submitted). The geospatial database coalition management component also comprises a coalition browser where the user can visualize a dynamic hierarchy of existing coalitions in the network, which can be classified according to the different elements of their contexts. The purpose of coalition is to support collaboration and partition the network according to various characteristics that facilitate the discovery of relevant sources.

Multi-View Augmented Concept (MVAC) component. This component is responsible for enriching the semantics of ontologies describing geospatial databases. The purpose of this component is to address the problem of knowledge representation, which is the problem of encoding the knowledge that human have about the reality. It is a fundamental issue for improving semantic interoperability because the more the semantics of data is rich and complete, the more users of different databases can understand each other, resolve semantic conflicts and avoid misinterpretation of data. Existing definitions of concepts are not always sufficient to represent all the semantic richness of geospatial concepts. In addition, some semantics may be implicit in the ontologies. We have previously proposed a new model for representing concepts, namely, the Multi-View Augmented concept (MVAC), where

each view represent the definition of the concept under a specific context, and the concept is augmented with the implicit dependencies that can be discovered between is features (spatial, temporal, thematic properties and relations) with rule mining techniques (Bakillah et al. 2010). An example of such dependency is between the spatial property *altitude* and the thematic property *flooding risk*: Altitude (*land*, *low*)→ Flooding Risk (*land*, *high*).

The MVAC component takes as input the ontologies of geospatial databases and generates ontologies with MVAC concept. The three main phases of the MVAC component is to (1) extract context with rule-based reasoning engine, (2) run the view extraction engine to extract a view for each context, and (3) augment the concepts with dependencies that were discovered between features. The description of the MVAC extraction and generation tool was provided in (Bakillah et al. 2010).

G-MAP Semantic Mapping Component. The semantic mapping component was developed to take as input the multi-view augmented concepts generated by the MVAC component, and automatically compute qualitative semantic relations among them (equivalence, inclusion, overlap, disjoint). The semantic mappings depend on the chosen context. This means that a user can select the most appropriate context to its situation (among the possible contexts of the chosen query concept) and the semantic mapping will take as input the definition of the concept that is valid in that context. The advantage is a context-dependent semantic interoperability solution that is tailored to user's needs. In addition, the spatial, temporal and thematic components of the semantic mappings are displayed to the user. This means that the semantic mapping is decomposed according to three dimensions. Each of the dimensions takes as input only the spatial, temporal or thematic features of the concepts. The global semantic mapping between two concepts is obtained by merging the three dimensions. The other contribution of this semantic mapping approach is its augmented matching feature. The augmented semantic mapping reasoning engine takes as input the semantic mappings computed by the regular semantic mapping reasoning engine and tries to improve it by running a structural matcher that compares dependencies that were extracted by the MVAC component. Because existing semantic mapping approaches and tools usually consider more simple definitions of concepts than the MVAC model, new semantic matching criteria for spatial and temporal features, views and dependencies were developed. The automatic computation of semantic mappings is ensured by logic inference rules stored accessible by each node. The reasoning process is based on the verification by the reasoning engine that all conditions stated in a mapping rule for a semantic relation to be true are verified.

Query Propagation Component. This component resolves the problem of determining, for a given query issued by a node, to which nodes this query should be propagated, and in what order, so that better expected query results are received first by the requestor. The result is an oriented propagation graph where nodes are the selected databases and directed arcs are paths along which the query is routed. The distinction of our approach with respect to other query propagation approaches (ex: Zhuge et al. 2004; Montanelli and Castano 2008) is that it does not rely on existing semantic mappings between concepts of databases' ontologies. Therefore, the propagation graph just determines the minimal number of databases that should be mapped, reducing the cost of semantic mapping process. With

the strategy manager, the user can select three different propagation strategies:

- The coalition-based strategy uses existing coalitions to propagate a query to set of databases that can answer the query, based on a comparison of the context of the query, and the context of the coalition. This strategy reproduces the ability of members of a social network to use existing organisations in the society.
- The context-based strategy determines the propagation order according to context affinity between query and databases; it is intended to be used inside the scope of a single coalition. This strategy reproduces the ability of members of a social network to use content to find people.
- The collective memory-based strategy uses the knowledge that users of databases have about queries that were previously answered to forward queries to relevant databases. This strategy reproduces the ability of members of a social network to use people to find content.

For each strategy, the strategy manager deploys different matcher for comparing contexts, queries and coalitions.

5. SCENARIO FOR DISASTER MANAGEMENT

We have developed a prototype implementation of the approach to demonstrate the applicability and characteristics of the approach in a short disaster management scenario. In this prototype implementation, the communication between nodes of the ad hoc network is ensured by the JXTA communication component, where JXTA is an open source peer-to-peer Java platform that simulates message exchange between peers, discovery and formation of peer groups[1]. The following scenario demonstrate the usefulness of the prototype to support an expert to find flooding risk zones during disaster response, in order to delineate safe evacuation routes. The query and its context can be formulated in OWL RDF/XML syntax as follow:

```
<owl:Class rdf:ID="FloodingRiskZone"/>
<owlx:ObjectProperty
owlx:name="InGeographicalLocation">
<owlx:domain owlx:class="FloodingRiskZone"/>
<owlx:range owlx:class="Ontario"/>
</owlx:ObjectProperty>
<owlx:ObjectProperty owlx:name="TimePeriod">
<owlx:domain owlx:class="FloodingRiskZone"/>
<owlx:range owlx:class="2010"/>
</owlx:ObjectProperty>
<owlx:ObjectProperty owlx:name="InDomain">
<owlx:domain owlx:class="FloodingRiskZone"/>
<owlx:range owlx:class="Hydrography"/>
</owlx:ObjectProperty>
<owlx:ObjectProperty owlx:name="Role">
<owlx:domain owlx:class="FloodingRiskZone"/>
<owlx:range
owlx:class="DelineateEvacuationRoute"/>
</owlx:ObjectProperty>
```

Before submitting the query, the expert seeks to find groups of database users that can collaborate toward flooding management in the targeted region. The expert runs the coalition mining algorithm and selects the parameter "role" to detect possible coalitions that can be form on the basis of

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[1] JXTA project. see http://www.jxta.org.

similar roles. The coalition mining process create a hierarchy of coalitions classified by roles: "*coalition for flooding management*", "*coalition for land use management*", etc. The expert can search the hierarchy with the coalition browser to find relevant coalition for its task, and add members of this coalition to its network acquaintances (Figure 2). The advantage of this coalition representation is that databases can form coalitions even if they describe different domains, which is typical in disaster management where stakeholders work in different areas of expertise.
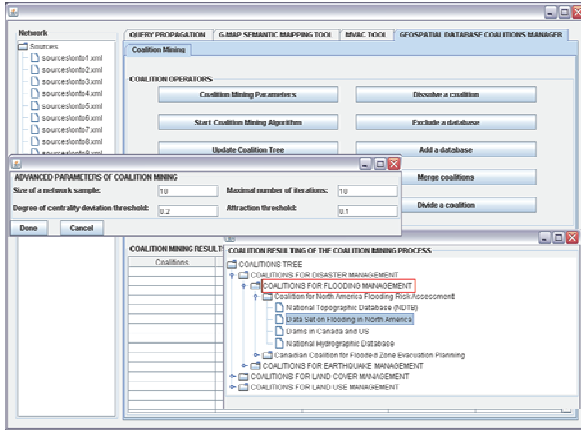

Figure 2. The interface of the Geospatial Database Coalition Manager

Before the expert formulates a query to submit to the network, he or she runs the MVAC extraction and generation tool to semantically enrich the concepts of its ontology. For instance, for the concept "*flooding risk zone*" selected from the ontology describing the database of the expert, two views are extracted for two functional contexts: "*disaster response*" and "*disaster preparation*". The expert can notice that the views which are valid in each of those contexts differ with respect to the definition of the spatiotemporal property "*spatial extent*" which is a *GML*: *MovingPolygon*, which semantic is defined by the spatial descriptors incorporated in the MVAC model (Figure 3).
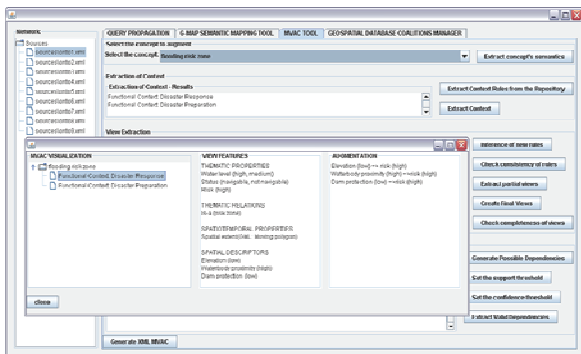

Figure 3. The interface of the MVAC tool

In the "*disaster response*" view, the spatial extent of the "*flooding risk zone*" is defined (in Description Logics syntax):

```
SpatialExtent ∩ ∃HasElevation.Low
∩ ∃WaterbodyProximity.High ∩ ∃DamProtection.Low
```

In the "*disaster preparation*" view, the same spatiotemporal property is defined as:

```
SpatialExtent∩
(∃HasElevation.Low∪∃HasElevation.Medium)∩
(∃WaterbodyProximity.High∪∃WaterbodyProximity.Me
dium)∩(∃DamProtection.Low∪∃DamProtection.Medium)
```

Thus, in different contexts, what is considered to be a risk zone is different because of the varying degree of emergency. In addition, the concept was augmented with the following dependencies: *Elevation* (*low*) → *risk* (*high*), *waterbody proximity* (*high*) → *risk* (*high*), *dam protection* (*low*) → *risk* (*high*), meaning that low elevation, proximity to a waterbody and low dam protection are risk factors.

The flooding management expert then formulates the above query which is propagated in the network according to the selected strategy. The ontologies of databases that are part of the computed propagation graph are mapped with G-MAP component with the query concept "*flooding risk zone*" according to the partial order defined by the oriented propagation graph. The resulting semantic mappings are displayed according to the thematic, spatial and temporal dimensions (Figure 4). This allows the user to consider the dimension that he or she considers a more relevant selection criterion. The impact of the augmentation with MVAC tool is displayed. In the scenario, the structural correspondence between two dependencies describing the query concept "*flooding risk zone*" and the concept "*flood hazard area*" of the National Topographic Database (NTDB) respectively was used to infer the correspondence between two properties "*elevation*" and "*ground level*" : *Elevation* (*low*) → *risk* (*high*) and *Ground level* (*low*) → *risk* (*high*). Finally, the G-MAP mapping visualization interface shows the spatiotemporal conflicts that were detected by G-MAP. In that case, the definitions of the spatial extent of the risk zone/hazard area are not equivalent. The detection of spatiotemporal conflict is crucial for avoiding misinterpretation of data. In that case, it means that hazard areas in the NTDB are not determined by taking into account the protection of dams, so the NTDB might contain less risk zones.
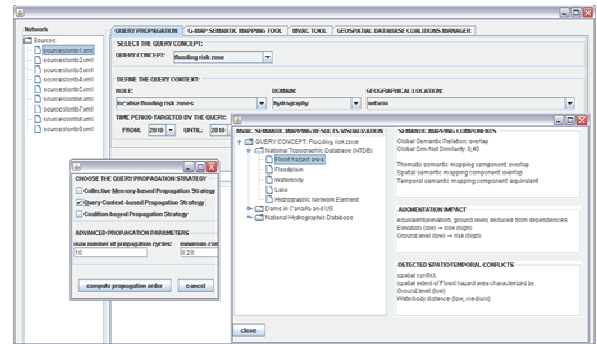

Figure 4. The interface of G-MAP tool and Real Time Query Propagation Tool

The G-MAP tool allows the user to determine what concepts of other geospatial databases of the network are correct candidates for its query. In summary, the user in a disaster management situation can retrieve relevant data with reduced risks of misinterpretation of data because of the deep comprehensive representation of concepts.

6. CONCLUSION

In this paper, it was demonstrated that real time semantic interoperability is a critical issue in disaster management. An architecture for a real time semantic interoperability approach in ad hoc networks of geospatial databases was proposed. This architecture integrates the components required to consider both constraints posed by geospatial semantics and constraints posed by dynamic, decentralized environment like ad hoc networks, including the formation of coalitions of geospatial databases according to relevant criteria for the geospatial domain, a rich knowledge representation, an augmented semantic mapping process that consider space, time and theme as distinctive components, and a multi-strategy query propagation approach. The prototype implementation of the architecture demonstrate the ability of the approach to support meaningful geospatial data sharing and reducing risks of misinterpretation of shared data in a disaster management situation where reliability of information and respect of time constraints are crucial. In future work, we aim at improving this architecture with a component that assesses the quality of the global real time semantic interoperability process, taking into account the quality of each separated process. This improvement would support the user in selecting best semantic interoperability strategies and therefore improve the soundness of decision making.

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