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Towards a Geographic Ontology Reference Model for Matching Purposes

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Abstract. *Ontologies and geographic ontologies are becoming important research and application fields for the geographic information systems (GIS) community. Although geographic ontologies (also known as spatial-temporal ontologies, geo-ontologies or geospatial ontologies) are becoming popular, a standard and complete model is still missing. The attempts for establishing standards are yet incipient, i.e., do not fulfill the actual needs. In this paper we propose a reference model for developing geographic ontologies, with the specific purpose of matching. The main idea is to extend the model for conventional, non-geographic, ontologies to make it suitable for describing the particularities of the GIS data and the relationships among them.*

Resumo. *Ontologias e, mais especificamente, ontologias geográficas, estão se tornando um importante campo de aplicação e pesquisa relacionado à comunidade de Sistemas de Informações Geográfica (SIG). Embora ontologias geográficas (também conhecidas por ontologias espaciais, ontologias espaço-temporais, geo-ontologias ou ainda ontologias geo-espaciais) vêm tornando-se populares, falta ainda um modelo completo e que seja adotado como padrão. As tentativas para estabelecimento de padrões são ainda incipientes, ou seja, não satisfazem completamente as necessidades atuais. Neste artigo nós propomos um modelo de referência para o desenvolvimento de ontologias geográficas, com o propósito especial de* matching *(casamento). A idéia principal é estender o modelo para ontologias não-geográficas, de modo a fazê-lo adequado para descrever as particularidades dos dados espaço-temporais e os relacionamentos entre eles.*

1. Introduction

Ontologies and geographic ontologies are becoming important research and application fields for the geographic information systems (GIS) community. Due to the particularities of the GIS data - geometry and location [Fonseca et al. 2003], and, eventually, temporal properties as well [Sotnykova et al. 2005], besides the usual descriptive attributes - a simple alphanumeric ontology (called here conventional ontology) is not expressive enough. It is like in the database field, where there are special types of databases for geographic data, called geographic databases, because conventional databases were not designed for holding these features. The ability to build proper geographic ontologies will facilitate their integration and, subsequently, will advance semantic interoperability, which has been acknowledged as a primary concern in geographic information science nowadays [Tomai and Kavouras 2004].

According to Spaccapietra et al. [Spaccapietra et al. 2004] space and time can meet ontologies in three different ways: (1) as the spatial domain specifying space, spatial elements and spatial relationships, or as the temporal domain, specifying time, temporal elements and temporal relationships; (2) as the implicit background to an application domain that relies on geographical data or; (3) to enrich the description of the concepts in the ontology, to represent their spatial and temporal location, in the same way spatio-temporal data models support the description of spatial and temporal features in spatio-temporal databases.

Although ontologies are being widely used by the GIS community, there is still a lack for an actual geographic ontology model (also know as spatial ontology, geo-ontology, spatio-temporal ontology or geospatial ontology). That is, the ontologies proposed and used at the moment are designed for conventional (descriptive), non-spatial purposes and the particularities of the geographic data, such as the geometry, temporality and topological relations are missing or poorly described. There are already some standard proposals (ISO 19109 and GML OWL encoding), but they have some limitations in terms of expressiveness, validation or easiness to use or extend. In other words, the attempts for establishing standards are yet incipient, i.e., do not fulfill the actual needs. The main limitation of these proposals is that they do not really hold the semantics of a geographic ontology. Instead, they basically define the syntax and the names for some geographic elements.

There are many fields in which geographic ontologies can be applied, such as building a common ground for describing the geographic phenomena, spatial reasoning, semantic annotation of maps, geographic information integration and retrieval, and so on. In this paper we are proposing a geographic ontology model specially designed for the purpose of geographic ontology matching, which is quite different from conventional ontology matching [Hess et al. 2007b]. This ontology is part of a wider project, in which we are developing a methodology for matching geographic ontologies at both the concept-level [Hess et al. 2006] and the instance-level [Hess et al. 2007a].

The reminder of this paper is structured as follows. In Section 2 we present some related work which try to define geographic ontology models. Our proposal for a geographic ontology reference model is presented in Section 3. Then, in Section 4 we show an example of an ontology built based on our reference model. Finally, conclusions and future work are discussed in Section 5.

2. Related Work

Maedche and Staab [Maedche and Staab 2000] state that an ontology should comprise the following: (a) Concepts, (b) the Lexicon, (c) Relations and (d) Axioms. Concepts are an integral part of an ontology as they stand for mental things of all possible things [Tomai and Kavouras 2004]. The Lexicon comprises the descriptions of the concepts, i.e., their definition in natural language. The semantic relations link two concepts in hypernym/hyponym relation and in the meronym/holonym relation as well. The relation as semantic properties refer to the properties of the concepts in the ontology. The axioms refer to constraints imposed on concept or relations.

Tomai and Kavouras [Tomai and Kavouras 2004] extend Maedche and Staab's definition of ontology by defining the components of a geographic ontology. They basically create some semantic properties to be associated to a concept when it represents a geographic concept: Spatiality, Temporality, Nature, Material/cover, Purpose and Activity. The first two are the ones that actually characterize a geographic ontology. Spatiality covers the relative spatial properties of the concept, such as topology, location, and the internal spatial properties, such as size and shape. Temporality is divided into time (period or instant) and condition/status.

Casati, Smith and Varzi [Casati et al. 1998] separate a geographic ontology in two parts: objects and relations. The geographic objects are specialized into physical, such as mountains, rivers and forests, and human, such as countries, cities, and so on. A geographic object is composed by a number of descriptive attributes and by a border. The relations can be of type mereology, location or topology. In a mereology association, a geographic object A *is part of* a geographic object B. The location relation associates a geographic concept with a set of coordinates, and a topology relation spatially associates two geographic concepts. Souza et al. propose an ontology to represent contextual information in geospatial data integration [Souza et al. 2006]. The ontology is composed by 5 contexts, as the authors present. Each one of it stores some kind of information. The main two are the *DataContext* and *AssociationContext*. The *GeospatialEntity* is the main concept of the *DataContext*, and contains the properties for geometric representation, location and some metadata. The *AssociationContext* has the information about the spatial association of the concepts and the semantic associations (degree of similarity) as well [Souza et al. 2006]. As weak points of these works we can point the absence of temporal aspects and the impossibility of representing non-geographic concepts.

Fu et al. [Fu et al. 2005] developed a geo-ontology restricted to geographic places, such as cities, countries, districts and so on. Each concept is described in terms of its names (can be multiple), geometry (called footprints by the authors) and some metadata. Furthermore, each place may be related to another by only one relation, the *containment relation*. Kolas et al. [Kolas et al. 2006] propose an architecture for *Geospatial Semantic Web* [Egenhofer 2002]. They define 6 ontologies, and one of them, called *Base Geospatial Ontology* is of interest in the context of this paper. It forms the ontological foundation of geospatial information by mapping some GML's elements to OWL, in order to link the geographic data with knowledge outside the geospatial realm [Kolas et al. 2006].

SWETO-GS [Arpinar et al. 2006] is a spatio-temporal ontology with three dimensions, namely thematic, spatial and temporal. The thematic dimension contains the concepts of a general domain such as people, places and organizations, or for a specific domain such as travel and transport. In that dimension there are both geographic and non-geographic concepts. The geospatial dimension stores the spatial data and relationships. The concepts are described in terms of their coordinates, translated from the thematic dimension. The temporal dimension stores the temporal relations that may occur between concepts. Finally, some metadata can be associated to the SWETO-GS ontology.

Bittner and Smith propose an ontological theory which contains resources to describe geographic processes and the concepts that participate therein [Bittner and Smith 2003]. For that purpose two (sub-)ontologies are presented, one describing the concepts with their properties, called SNAP, and one describing the processes and their parts and aggregates, called SPAN. SNAP entities are described in terms of their properties, spatial relations and conventional relations, while SPAN entities are described also considering time.

3. The reference model

Any ontology can be defined as a 4-tuple $O =< C, P, I, A >$, where C is the set of concepts, P is the set of properties, I is the set of instances, and A is the set of axioms [Scharffe and de Bruijn 2005][1]. A concept $c \in C$ is any real world phenomenon of interest to be represented in the ontology and is defined by the term t that is used to nominate it. The name of a concept is given by the unary function $t(c)$. A property $p \in P$ is a component that is associated to a concept c with the goal of characterizing it, but is defined outside the scope of a concept. It can be a data type property, which means that its range is a data type, such as string, integer, double, etc. or an object type property, meaning that the allowed range values are other concepts. A data type property can be viewed as a database attribute, while an object type property is like a database relationship.

The context of a concept $c \in C$ is defined as the set of properties P (each one given by the unary function $p(c)$) related to it, as well as by the set of axioms A, representing the generalization/specialization relations as well as the restrictions (each one given by the unary function $x(c)$). Formally, the context of a concept can be defined as:

$$ctx(c) =< t(c), \{p(c)\}, \{x(c)\} >$$

An instance $i \in I$ is a particular occurrence of a concept c, with values for each property p associated to the concept and an unique identification. Thus, an instance may be defined as

$$i =< t(c), t(i), VP >,$$

where $t(c)$ is the concept being instantiated, $t(i)$ is the instance unique identifier (name) and VP is the set of values for the properties belonging to the context of the instantiated concept.

At last, an axiom describes an hierarchical relationship between concepts, or provides an association between a property and a concept (through the property domain or through a concept restriction), or associates an instance with the concept it belongs.

3.1. Geographic concept

A spatio-temporal object (STOBJ) as defined by Xu et al. [Xu et al. 2006] has spatial and temporal properties as well. The former encompass geometries and the spatial relationships such as distance, position, topological, and so on. Temporal properties are,

[1]This definition is based on the OKBC model [Chaudhri et al. 1998]. In the original work, instead of P (properties) it was R (relations)

basically, instant and period. Based on these properties, a spatio-temporal ontology is a normative system describing spatio-temporal objects and relationships between them.

Following this premise, a conventional ontology is not expressive enough to handle the particularities of geographic phenomena. Thus, we define a geographic ontology, which is an extension of a conventional ontology. It is also a 4-tuple $O =< C, P, I, A >$, where C is the set of concepts, P is the set of properties, I is the set of instances, and A is the set of axioms.

A concept $c \in C$ is classified into domain concept, such as a *River*, a *Park* or a *Building*; geometry concept, such as *Point*, *Line* or *Polygon*; or time concept, specialized in *instant* and *period*. Furthermore, a geographic domain concept gc is a specialization of a domain concept representing a geographic phenomenon, as depicted in Figure 1. A geographic domain concept is defined as being a domain concept with an axiom saying that it must be associated to, at least, one geometry concept, through a geometric relationship property, which is explained in the following. The geometry plays a fundamental role on defining the possible spatial relationships the concept may have.

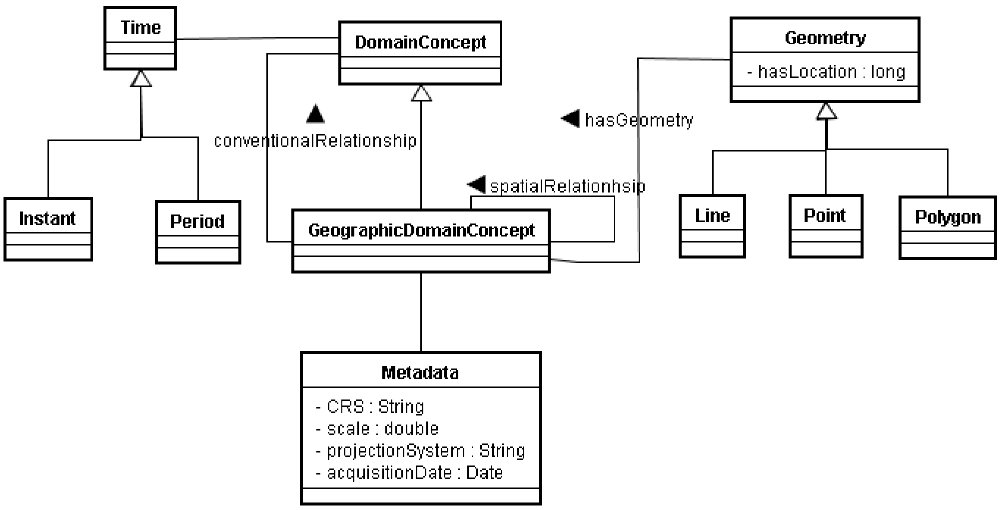

Figure 1. Types of concepts of the geographic ontology reference model

3.2. Properties in a geographic ontology

In an ontology a property can be defined by itself, i.e., outside the context of a concept. However, for matching purposes, a property is relevant when associated to a concept, directly in its domain or through a restriction. For this reason the property is always considered into the context of a concept. In a geographic ontology, each property $p \in P$ can be of one of five possible types: conventional, spatial relationship, geometric relationship, positional or temporal. Formally, it can be defined as a 4-tuple

$$p =< t(p), pd, minCard, maxCard >,$$

where $t(p)$ is the function which gives the property's name, pd is the property domain (detailed in the following) and $minCard$ and $maxCard$ are, respectively, the property's minimum and maximum cardinalities.

A conventional property may be even a data type property or an object type property. In the first case it represents an attribute of a domain concept. In the second case it represents an association between a domain concept (geographic or not) with a non-geographic domain concept, which we call conventional relationship (cr).

An attribute $a \in P$ is a special type of property to which the minimum and maximum cardinalities are not relevant, and the domain is a data type (dtp), such as string, integer, and so on. Thus, it can be simplified as a tuple of the form

$$a =< t(p), dtp >$$

A conventional relationship, on the other hand, is a property $p =< t(p), pd, minCard, maxCard >$ with the restriction that the property's domain pd is a domain concept, identified as $t(c_x)$. Furthermore, the concept identified by $t(c_x)$ cannot be a geographic domain concept, i.e., $cr = (p \in P|(c_x : \neg gc))$

A spatial relationship property sr (topological, directional or metric) is always an object type property $p =< t(p), pd, minCard, maxCard >$, and represents an association between two geographic domain concepts, i.e, can appear only in the context of a geographic domain concept. The spatial relationships have a pre-defined semantics and are already standardized in the literature [Egenhofer and Franzosa 1991] and by the Open GIS Consortium (OGC). Formally, we define a spatial relationship as $sr = (p \in P|(c_x : gc))$

A geometric relationship property ge (always an object type property $p =< t(p), pd, minCard, maxCard >$) is an association between a geographic domain concept with a geometry concept geo, i.e., $ge = (p \in P|(c_x : geo) \wedge minCard = 1)$

A positional property pos is a data type property that must be associated to a geometry concept, to give its location (set of coordinates).

Finally, a temporal relationship property tr is an association between a domain concept and a time concept, i.e., $tr = (p \in P|(c_x : time))$

These relationships allow one to answer queries such as:

- With which instances i_x a given instance i has borders;
- Which concepts gc_x may cross the concept gc;
- How far one instance i is from an instance i_x.

3.3. Geographic and geometry concepts as axioms

The set of axioms A describes the hierarchical (IS-A) relationships between concepts as well as provides associations between properties and concepts, and relates instances with the concepts they belong to. A hierarchy $h \in A$ is a binary relation of type $h(c, c_x)$, where c_x is the superclass of the concept c.

With the definitions above, we can now formally define a geographic concept gc through a restriction axiom, as:

$$gc = (c \in O|\exists p \in P \wedge p : ge \wedge t(p) = "hasGeometry" \wedge minCard = 1),$$

where ge is the geometric property.

A geometry concept can also be formally defined as a concept with a restriction axiom stating it must have associated at least one positional property pos.

$$geo = (c \in O | \exists p \in P \wedge p : pos \wedge t(p) = "hasLocation" \wedge minCard = 1),$$

where pos is the positional property.

3.4. Geographic region and instance

An instance of a concept is defined by the property values associated to a concept. An instance $i \in O$ is a triple of the form $i =< t(c), t(i), VP >$, where

- $t(c)$ is the name of the concept being instantiated.
- $t(i)$ is the unique identifier of an instance (instance name).
- VP is the set of values for the properties. Each one of the elements is represented by the binary function $vp(t(p), val)$, where $t(p)$ is the property name and val is the value associated to the property for that instance.

A geographic instance gi is an extension of an instance i. As a geographic instance must be associated to, at least, one instance of a geometry concept, the value of the positional property (*hasLocation*) gives the spatial position (coordinates) of that geographic instance. A geographic instance $gi \in O$ is, thus, a 4-tuple of the form $gi =< t(c), t(i), VP, vMD >$, where

- $t(c)$ is the name of the concept being instantiated.
- $t(i)$ is the unique identifier of an instance (instance name).
- vP is the set of values for the properties. Each one of the elements is represented by the ternary function $vp(t(p), val)$, where $t(p)$ is the property name and val is the value associated to the property for that instance.
- vMD is the set of metadata values associated to the instance. Each one of the metadata values is represented by a binary function $vmd(t(md), val)$, where $t(md)$ is the metadata and val is the value set for that geographic instance.

Georeferencing is the set of geographic coordinates of the vertices or planar coordinates in a given coordinate system. Additionally, it has the information of the cartographic projection. It applies only to the geographic instances, not to the concept definitions. The georeferencing information is stored by the metadata, and is thus given to an instance by the vMD component (association holding between a geographic instance gi and the metadata).

The set of instances of a concept c is given by I, and thus $i \in I$. Figure 2 shows graphically the types of instances we can have in our ontology and how one relates to the other. It is important to notice, however, that *GeographicRegion*, *RegionRepresentation* and *Metadata* are not concepts described in an ontology, but concepts belonging to the reference model for matching purposes.

As it is possible to infer, $I =< R, \{i\} >$, where R is a new ontology element we are introducing into our ontology. It represents the region covered by the set of instances stored in the ontology. Furthermore, it generalizes the metadata values associated to the instances. The *GeographicRegion* plays an important role in the matching process for which this reference model is designed to. Basically, the two main reasons for creating the notion of geographic region are:

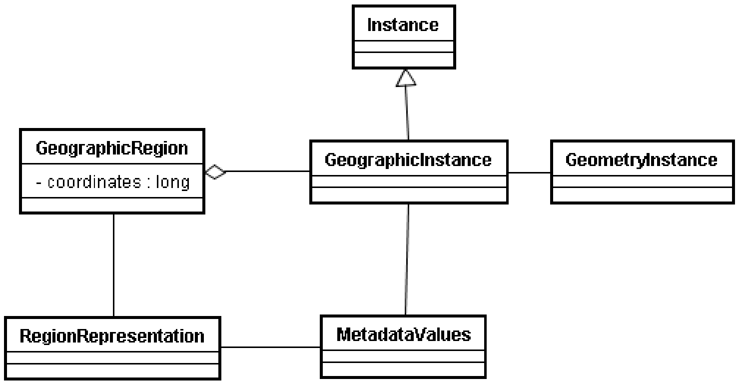

Figure 2. Types of instances of the geographic ontology reference model

- To create the notion of region similarity, and, as a consequence, to measure how similar are two ontologies not at the instance granularity, but at the instance set granularity;
- To accelerate the process of instance similarity assessment by eliminating the pairs of instances which are geographically disjoint.

3.5. Metadata

As already stated, the $metadata$ class and its instantiation $metadaValues$ do not represent concepts and instances defined by the ontology designer. Instead, they provide additional information about them, such as the coordinate reference system, the projection scale, the data's capture date, among others. These information is crucial in the matching process, in order to avoid incorrect interpretations due to differences on the metadata. For example, a concept that may be associated to a geometry specialization of $point$ in a low detailed scale, such as 1:500.000. However, the same concept may be associated to a $polygon$ concept if in a more detailed scale, such as 1:25.000. The same applies to instances. The values for an instance's coordinates vary if are described using $< latitude, longitude >$ reference system or if they are described using $polar$ coordinate reference system.

3.6. Operations

In the reference model we are proposing in this research two operations may be performed over an ontology: the creation/insertion of concepts and the definition of hierarchical relationships between concepts.

As our target is the matching of two geographic ontologies, it may happen that at least one of the input ontologies contains only the explicit definition of the instances, i.e., without the explicit declaration of the concept they instantiate and its structure. In this case new concepts are added to the input ontology through the information extracted from the instances. The concept name is obtained from the $t(c)$ component of the instance triple $i =< t(c), t(i), VP >$ (or 4-tuple $gi =< t(c), t(gi), VP, vMD >$ in case of a geographic instance) and the properties are given by the union of the properties the instances have values for.

Once the concepts are defined from their instances, it is possible to define their names ($t(c)$) and properties (attributes and relationships between concepts as well), but not the hierarchy among them. For that purpose, the operation of taxonomy definition is performed, consisting on searching into a reference ontology, also defined according to the reference model proposed here, to identify the hierarchical relationships among the concepts created for the input ontology.

4. Example of an ontology based on the reference model

In this section we present a geographic ontology we developed based on the reference model we proposed. The example, however, does not exploit all the expressiveness power of the reference model, specially in terms of the temporal aspects. Furthermore, the metadata do not appear explicitly in the ontology. Figure 3 graphically depicts the concepts and the instances of the ontology, as well as the properties associated to the concepts. It is important to notice that both geographic and non-geographic concepts can be defined using the reference model.

The rectangles with continuous lines represent concepts, the ellipses the properties representing attributes associated with a concept and the dashed rectangles the instances belonging to a concept. The arcs linking two concepts correspond to the properties which represent relationships holding between them, while the isa labeled arrows are the taxonomic relationships (axioms) between two concepts, in which one is the specialization of the other.

Figure 4 presents the encoding of the example ontology described in a generic language, somehow structurally similar to description logics (DL). However, it is important to clarify that the syntax is completely different from DL and is not from any existing language. We try to use the DL format with a natural language syntax, just to formalize a little the ontology.

5. Conclusions and future directions

Ontologies are becoming the standard mean to describe resources to be shared with semantics. With geographic information is not different. Many ontologies are being proposed. However, due to the absence of a wide accepted standard reference model for a spatio-temporal ontology, the comparison of the concepts and instances of these ontologies is a very hard, time consuming and error prone task. As these ontologies may be defined using different models, before matching their concepts and instances, it is necessary to identify the corresponding elements used in their definition and how they relate to each other. In other words, a meta-matching of the ontologies' models is needed.

To solve this gap, we proposed here a geographic reference ontology model, for the specific purpose of geographic ontology matching. By extending the formally defined model it is possible to create concepts, hierarchies, properties and associate them to concepts and instances, just as for a conventional, non-geographic ontology. Then, we defined some properties and axioms specific for the geographic field, such as geometry, spatial relationships (topology, directional and metric), spatial position and temporality. Finally, we established the association between instances and metadata, which are fundamental information for the geographic data. The presented example showed how to use the reference model to define a geographic ontology.

As future works we plan to develop a more sophisticated ontology based on the reference model, in order to make use of all its potentiality, including geographic concepts and non-geographic concepts, temporal properties and more spatial relationships. We also plan to use more the metadata component of the instances. Furthermore, the current reference model allows the definition of temporal concepts, but not temporal properties. We thus plan to extend it to support temporality for properties.

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References

Arpinar, B., I, Sheth, Amit, Ramakrishnan, Cartic, Usery, L., E, Azami, Molly, Kwan, and Mei-Po (2006). Geospatial ontology development and semantic analytics. *Transactions in GIS*, 10(4):551–575.

Bittner, T. and Smith, B. (2003). Granular spatio-temporal ontologies. In *Proceedings of the AAAI Spring Symposium on Foundations and Applications of Spatio-Temporal Reasoning (FASTR).*

Casati, R., Smith, B., and Varzi, A. C. (1998). Ontological tools for geographic representation. In Guarino, N., editor, *Formal Ontology in Information Systems*, pages 77–85. IOS Press.

Chaudhri, V. K., Farquhar, A., Fikes, R., Karp, P. D., and Rice, J. (1998). OKBC: A programmatic foundation for knowledge base interoperability. In *AAAI/IAAI*, pages 600–607.

Egenhofer, M. J. (2002). Toward the semantic geospatial web. In Voisard, A. and Chen, S.-C., editors, *ACM-GIS*, pages 1–4. ACM.

Egenhofer, M. J. and Franzosa, R. D. (1991). Point set topological relations. *International Journal of Geographical Information Systems*, 5:161–174.

Fonseca, F. T., Davis, C. A., and Camara, G. (2003). Bridging ontologies and conceptual schemas in geographic information integration. *GeoInformatica*, 7(4):355–378.

Fu, G., Jones, C. B., and Abdelmoty, A. I. (2005). Building a geographical ontology for intelligent spatial search on the web. *Databases and Applications (DBA2005)*, pages 167–172.

Hess, G. N., Iochpe, C., and Castano, S. (2006). An algorithm and implementation for geoontologies integration. In *Prof. of VIII Brazilian Symposium on Geoinformatics (GEOINFO'06).*

Hess, G. N., Iochpe, C., and Castano, S. (2007a). Geographic ontology matching with ig-match. In Kollios, G., Papadias, D., and Zhang, D., editors, *SSTD*, Lecture Notes in Computer Science. Springer.

Hess, G. N., Iochpe, C., Ferrara, A., and Castano, S. (2007b). Towards effective geographic ontology matching. In *Second International Conference on GeoSpatial Semantics (GeoS 2007).*, Lecture Notes in Computer Science. Springer.

Kolas, D., Dean, M., and Hebeler, J. (2006). Geospatial semantic web: architecture of ontologies. In *2006 IEEE Aerospace Conference*.

Maedche, A. and Staab, S. (2000). Semi-automatic engineering of ontologies from text. In *Proceedings of the Twelfth International Conference on Software Engineering and Knowledge Engineering (SEKE'2000)*.

Scharffe, F. and de Bruijn, J. (2005). A language to specify mappings between ontologies. In Chbeir, R., Dipanda, A., and Yétongnon, K., editors, *SITIS*, pages 267–271. Dicolor Press.

Sotnykova, A., Cullot, N., and Vangenot, C. (2005). Spatio-temporal schema integration with validation: A practical approach. In Meersman, R., Tari, Z., Herrero, P., Mendez, G., Cavedon, L., Martin, D., Hinze, A., Buchanan, G., Perez, M. S., Robles, V., Humble, J., Albani, A., Dietz, J. L. G., Panetto, H., Scannapieco, M., Halpin, T. A., Spyns, P., Zaha, J. M., Zimanyi, E., Stefanakis, E., Dillon, T. S., Feng, L., Jarrar, M., Lehmann, J., de Moor, A., Duval, E., and Aroyo, L., editors, *OTM Workshops*, volume 3762 of *Lecture Notes in Computer Science*, pages 1027–1036. Springer.

Souza, D., Salgado, A. C., and Tedesco, P. A. (2006). Towards a context ontology for geospatial data integration. In Meersman, R., Tari, Z., and Herrero, P., editors, *OTM Workshops (2)*, volume 4278 of *Lecture Notes in Computer Science*, pages 1576–1585. Springer.

Spaccapietra, S., Cullot, N., Parent, C., and Vangenot, C. (2004). On spatial ontologies. In *VI Brazilian Symposium on GeoInformatics (GEOINFO 2004)*.

Tomai, E. and Kavouras, M. (2004). From "onto-geonoesis" to "onto-genesis": The design of geographic ontologies. *GeoInformatica*, 8(3):285–302.

Xu, W., Huang, H.-K., and Liu, X.-H. (2006). Spatio-temporal ontology and its application in geographic information system. In *Fifth International Conference on Machine Learning and Cybernetics*, pages 1487–1492.

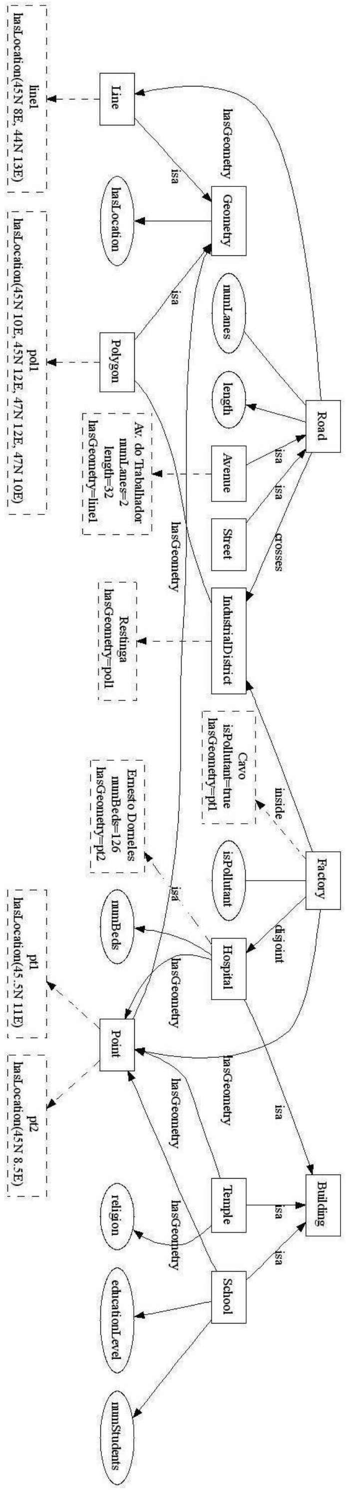

Figure 3. An example of ontology O

$$
\begin{array}{lll}
C & = & Road, Street, Avenue, Factory, IndustrialDistrict, Building, \\
 & & Hospital, Temple, School \text{ (domain)} \\
 & & Geometry, Line, Polygon, Point \text{ (geometry)} \\
P & = & numLanes, length, isPollutant, numBeds, religion, \\
 & & educationLevel, numStudents \text{ (conventional)} \\
 & & disjoint, crosses, inside \text{ (spatial)} \\
 & & hasGeometry \text{ (geometric)} \\
 & & hasLocation \text{ (positioning)} \\
A & = & isa(Polygon, Geometry) \\
 & & isa(Point, Geometry) \\
 & & isa(Line, Geometry) \\
 & & isa(School, Building) \\
 & & isa(Hospital, Building) \\
 & & isa(Temple, Building) \\
 & & isa(Street, Road) \\
 & & isa(Avenue, Road) \\
 & & hasGeometry(Road, Line) \\
 & & hasGeometry(IndustrialDistrict, Polygon) \\
 & & hasGeometry(Factory, Point) \\
 & & hasGeometry(Temple, Point) \\
 & & hasGeometry(School, Point) \\
 & & hasGeometry(Hospital, Point) \\
 & & crosses(Road, Some(IndustrialDistrict)) \\
 & & disjoint(Hospital, Factory) \\
 & & inside(Factory, Some(IndustrialDistrict)) \\
 & & isPollutant(Factory, boolean) \\
 & & educationLevel(School, String) \\
 & & numStudents(School, integer) \\
 & & religion(Temple, String) \\
 & & numBeds(Hospital, integer) \\
 & & numLanes(Road, integer) \\
 & & length(Road, double) \\
 & & hasLocation(Geometry, double) \\
I & = & instanceOf(pol1, Polygon) \\
 & & hasLocation(pol1,' 45N, 19E, 45N12E, 47N12E, 47N10E') \\
 & & instanceOf(pt1, Point) \\
 & & hasLocation(pt1,' 45.5N11E') \\
 & & instanceOf(pt2, Point) \\
 & & hasLocation(pt2,' 45N8.5E') \\
 & & instanceOf(line11, Line) \\
 & & hasLocation(hasLocation,' 45N8E, 44N13E') \\
 & & InstanceOf(AvenidaDoTrabalhador, Avenue) \\
 & & numeLanes(AvenidaDoTrabalhador, 2) \\
 & & hasGeometry(AvenidaDoTrabalhador, line1) \\
 & & instanceOf(Restinga, IndustrialDistrict) \\
 & & hasGeometry(Restinga, pol1) \\
 & & instanceOf(Cavo, Factory) \\
 & & isPollutant(Cavo, true) \\
 & & hasGeometry(Cavo, pt1) \\
 & & instanceOf(ErnestoDorneles, Hospital) \\
 & & numBeds(ErnestoDorneles, 111l) \\
 & & hasGeometry(ErnestoDorneles, pt2) \\
 & & inside(Cavo, Restinga) \\
 & & crosses(AvDoTrabalhador, Resting)
\end{array}
$$

Figure 4. Example of ontology defined according to the proposed reference model