ONTOLOGICAL IMPEDANCE IN 3D SEMANTIC DATA MODELING

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ABSTRACT:

An impedance mismatch exists between spatial data models and spatial ontologies, between the language of geometric representations and the language of specific application domains. We call it ontological impedance. Overcoming ontological impedance is a difficult task, since various problems are involved, like the coherence between the semantic and the geometric levels, the abstraction from various levels of geometric detail, the aspects of knowledge representation that constitute a semantic enrichment of current models. Various aspects have to be integrated in the representation of concepts at the semantic level, like the spatial, the temporal, the functional aspects. Overcoming ontological impedance means representing and reasoning with knowledge at the semantic level, shifting the attention from the geometric level to its conceptual counterpart.

1. INTRODUCTION

Current 3D data models and analysis methods are borrowed from CAD/CAM applications, computer graphics, and computer vision. There is no strong tradition in 3D GIS. It is unavoidable that existing 3D spatial data models are mostly oriented to visualization (and not to spatial analysis). CityGML is a geographic standard adopted by OGC that is well suited to the 3D representation of urban environments from a spatial analysis point of view (Kolbe, 2010). CityGML is made up of two distinct hierarchies, one semantic and one geometric, which need to maintain their respective coherence. Spatio-semantic coherence is an important issue that needs to be enforced between the semantic hierarchy of classes and the geometric hierarchy (Stadler and Kolbe, 2007).

In (Stadler and Kolbe, 2007), authors suggest that the introduction of spatial integrity constraints can be useful to test the correctness of geometrical representations, e.g. the fact that faces must be connected in the boundaries to form a volume, and, if they are thought at the semantic model, constraints can validate domain-specific aspects, e.g., a window must be inside a wall surface. Semantic relations now present in CityGML (Kolbe, 2010) are the generalization (is_a relation), e.g., SecondaryRoad is_a Road, the aggregation (is_ part_of relation), e.g., Wall is_part_of Building, and the semantic/geometric link (relation has_type), e.g., RoofSurface has_type Polygon.

To foster semantic interoperability (Worboys and Deen, 1991), 3D urban environments need to be modeled at the conceptual level, including entities, their attributes, the spatial constraints and rules that govern their existence, and the relations between entities. Generally, if conceptual entities have geometric representations, a semantic relation between entities implies one or more corresponding geometric relations.

Conceptual modeling is independent of various geometric representations. In particular, it is independent of the dimension of the embedding space: e.g., modeling how cars interact with roads is independent from the fact that we could use a 2-D spatial representation of cars and roads or a 3-D spatial representation. In fact, the conceptual (semantic) model is not restricted to a single data representation: therefore, multiple geometric representations can correspond to a single semantic model.

In this paper, we see the need of an object (entity)- based approach to spatial data modeling that takes into account the 3-D nature of entities from the beginning of the modeling phase. We push forward the need of spatio-semantic relations as the main semantic enrichment to be done in current models such as CityGML. In Section 2, we explain our motivations and in Section 3 we illustrate an example of approach in OWL 2. Section 4 draws short conclusions.

2. SPATIO-SEMANTIC RELATIONS IN 3D MODELING

Current conceptual approaches for GIS modeling were ingrained with the 2-D view: it was the conceptualization that could be considered intrinsically two-dimensional. We never described a road thinking to it as a 3-D object: it was always a 2-D object (or even 1-D in most cases). Therefore, the semantics of a road as a 3-D object has never been described at the conceptual level. We miss a conceptualization of the road as a 3D object, while it would be very useful to describe roads as volumes, e.g., to describe various types of road connections or to model the maximum height of an underpass.

An urgent research issue is about a remaking of all the progresses that were made on 2-D data models towards 3-D data models. Talking about topological relations, not only the models about topological relations about solids have received less attention in the literature than topological relations about regions, but even the models for topological relations between regions need to be remade: the topological relations between 2-D regions are different if embedded in 3-D space. For example, if two lines in 2-D space are disjoint, it means that they are not connected, while two lines in 3-D space could be disjoint and still have a kind of connection (e.g., two rings forming a chain). There are topological properties that are simply (and obviously) not considered in models for topological relations in the plane. Some models for spatial relations that were extended or are easily extendable to 3D space are, e.g., for topological relations between 3D objects (Clementini et al., 1993; van Oosterom et al., 1994; Zlatanova, 2000; Billen et al., 2002) and projective relations between 3D objects (Billen and Clementini, 2006).

Another big issue which should be faced is the need of structuring a semantic model for objects in 3D space in a “multi-level” ontology. We distinguish the entity level from the geometric level: each level must hold its own description of objects, relations, and integrity constraints. Let us exemplify the latter concept. Most conceptual approaches for spatial data modeling consider geographic entities (e.g., roads, building) and geometric relations that can apply to them. For example, a typical conceptual model of a road network would state that the admissible topological relations between two roads are “touch”, “cross”, and “disjoint” (excluding “inside”, “contains”, or “overlap”). This mixed view relates the entities by using the topological relations that apply to their geometric representations. In the view that we push forward in this paper, at the entity-level of the ontology, spatial relations among entities are expressed in context-based terms, e.g., by saying that roads can “have a junction” or “intersect” or whatever term is better suited to express the spatial relation between two roads in a given context.

We keep separate the geometric level of the ontology, which can be put into correspondence with the upper-level (entity level) via a mapping. At the geometric level, the topological relations can describe the interaction between geometric features. The geometric level can actually be thought of as to be based on multi-representations. The road entities can be mapped to a 2-D geometric representation where they are represented by polylines and the topological relations by existing models, or they can be mapped to a given 3-D geometric representation where they are represented by surfaces and volumes and the topological relations are taken from a 3D set of relations.

On this distinction between spatial relations at the conceptual level and spatial relations at the geometric level, another example follows. Let us consider buildings and the following spatial relations between them:

1. Building A is inside building B: A is a part of B or A is a smaller building that is located inside an area surrounded by B;
2. Building A and building B are connected: buildings are close to each other (not necessarily touching) and it is possible to walk from A to B without going back to the street;
3. Building A and building B are bordering: buildings have a wall or other part in common but it is not possible to go directly from A to B;
4. Building A and building B are neighboring: buildings are located in adjacent areas but don’t have a physical connection;
5. Building A and building B are close: they are at walking distance;
6. Building A and building B are distant: an effort is needed to move from A to B (in a given context).

The above entity-level ontology of binary spatial relations between buildings could find many corresponding spatial relations at the geometric level, where multiple representations of the same scenario exist. The spatial relations that translate the entity level concept to a given geometric representation could be not so obvious to define. For example, the first spatial relation (“building A is located inside building B”) could be translated to various embedding spaces: e.g., for a 2D space, the geometric level relation could correspond to “region A’ is contained in region B’ or region A’ is contained in the convex hull of region B’”. Regions A’ and B’ are the 2D representations of buildings A and B, respectively.

Other examples of semantic relations (e.g., from a traffic network (Métral et al., 2009)) could be “Bus line 14 crosses the Northern part of Milan” or “There is a bus stop near the crossing of roads A and B”. The following class relations could be extracted from those relations: “BusLine cross CityPart” and “BusStop near CrossRoad”. These new semantic relations must be coherent with the geometric model as well. Class relations can be used also as semantic constraints that are able to define subclasses (Tarquini and Clementini, 2008). For example, from a class River, a class TributaryRiver can be defined as the set of rivers that have the ending point inside another river.

Spatio-semantic coherence is an important issue that needs to be enforced between the semantic hierarchy of classes and the geometric hierarchy (Stadler and Kolbe, 2007). The relations at the semantic level can be used for data validation purposes. In (Stadler and Kolbe, 2007), authors suggest that the introduction of spatial integrity constraints can be useful to test the correctness of geometrical representations, e.g. the fact that faces must be connected in the boundaries to form a volume, and, if they are thought at the semantic model, constraints can validate domain-specific aspects, e.g., a window must be inside a wall surface. Semantic relations now present in CityGML (Kolbe, 2010) are the generalization (is_a relation), e.g., SecondaryRoad is_a Road, the aggregation (is_ part_of relation), e.g., Wall is_part_of Building, and the semantic/geometric link (relation has_type), e.g., RoofSurface has_type Polygon.

Modeling semantic relations goes a step forward the overcoming of ontological impedance, by ensuring independence from the specific geometric relations’ model that is used in the geometric part. For example, the semantic relation “Building connected Road” could be translated with the topological relation “meets” of the 9-intersection model (Egenhofer and Herring, 1990) or the relation “touch” of the CBM (Clementini, Di Felice et al., 1993). Multiple representations are dealt with in CityGML (named Level Of Detail (LOD)), where more geometric models can correspond to a single semantic model. The spatio-semantic relations among concepts have to be coherently represented in various geometric models corresponding to LODs. For example, if two roads have a junction, the corresponding spatial relation at the geometric level depends on the spatial data type representing roads, which could be a polyline, a region, or a volume.

Another important group of spatial relations are directional and visibility relations (Tarquini et al., 2007). Especially in 3D applications for wayfinding, it is important to describe the directional relations between city objects in various frames of reference (Retz-Schmidt, 1988): absolute frames of reference (e.g., an object to the North of a city), intrinsic frames of reference (e.g., an object in front of a church), and relative frames of reference (e.g., an object which is met by a driver to the left of his path) (Tarquini and Clementini, 2007).

The last issue on semantic enrichment that we mention is the modeling of spatial data uncertainty and approximate spatial relations. The majority of models for representing uncertain geographical objects is related to 2D space (Clementini, 2008). There is an obvious need to extend those models to 3D space: for example the spatio-semantic relation between a tourist walking in the street and the restaurant visible to his/her left side could be modeled at the geometric level as an approximate relation between uncertain spatial objects.

3. SAMPLE ONTOLOGY

As an example, let us consider the realization in OWL (W3C Recommendation, 2009) of a sample extended ontology, based on CityGML. Given the classes `SemanticSpatialRelation`, `_CityObject`, and `_Geometry`, we have:

`BuildingSpatialRelation ⊆ SemanticSpatialRelation`

`_Solid ⊆ _GeometricPrimitive ⊆ _Geometry`

`_CityObject ⊆ _AbstractBuilding ⊆ Building`

The object property `hasSpatialRelation` has as a domain the CityGML class `_CityObject` and as codomain the semantic relation `SemanticSpatialRelation`. The second property `semanticSpatialRelationProperty` links the class `SemanticSpatialRelation` to a second object of the class `_CityObject`. Following the syntax of descriptive logics, we have:

`Dom(hasSpatialRelation, _CityObject)`

`Rng(hasSpatialRelation, SemanticSpatialRelation)`

`Dom(semanticSpatialRelationProperty, SemanticSpatialRelation)`

`Rng(semanticSpatialRelationProperty, _CityObject)`

To specify the concrete relation between two buildings, we consider:

`buildingSpatialRelationProperty ⊆ semanticSpatialRelationProperty`

To define some of the possible semantic spatial relations between two buildings, we consider a subset of the relations introduced in Section 2:

`connected ⊆ semanticSpatialRelation`

`inside ⊆ semanticSpatialRelation`

`neighboring ⊆ semanticSpatialRelation`

`distant ⊆ semanticSpatialRelation`

Then, we consider another hierarchy of properties starting from geometricSpatialRelation. Considering a well-known classification of spatial relations, we have:

`topologicalRelation ⊆ geometricSpatialRelation`

`metricRelation ⊆ geometricSpatialRelation`

`projectiveRelation ⊆ geometricSpatialRelation`

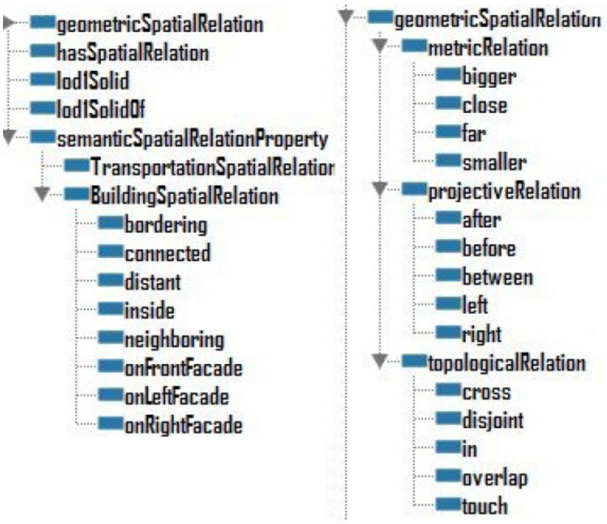

Figure 1. Visualization with Protégé of the object property hierarchies.

In Figure 1, we summarize the hierarchies defined till now. Now, it is necessary to express in OWL the link between the semantic and geometric parts. For example, restricting the representation to LoD1 of CityGML, the semantic spatial relation `connected` between two buildings could be put into correspondence with the topological relation `touch` between two solids that represent them.

A new functionality introduced in OWL 2 can solve this problem by allowing the construction of property chains. This functionality descends from some description logics, such as SROIQ(D_n) (Horrocks et al., 2006). Referring to the diagram of Figure 2, we can see the interaction between classes and properties.

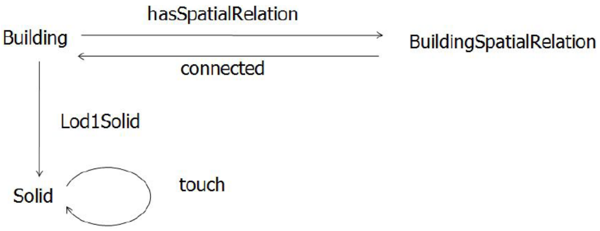

Figure 2. Classes and properties for the semantic relation `connected`.

The semantic relation `connected` between two buildings is realized with the intermediate class `BuildingSpatialRelation` and the chain of properties `hasSpatialRelation` and `connected`. The `touch` property must link two objects of the class `_Solid` that belong to the two buildings that are connected. To this end, we need both the relation `Lod1Solid` and its inverse `Lod1Solid`$^{-}$. The relation between semantics and geometry is therefore expressed with a composite property of `Lod1Solid`$^{-}$, `hasSpatialRelation`, `connected`, and `Lod1Solid`. In description logics syntax, we have:

`Lod1Solid`$^{-}$ ° `hasSpatialRelation` ° `connected` ° `Lod1Solid ⊆ touch`

In OWL, we have:

```
ObjectProperty: touch

SubPropertyOf: topologicalRelation

SubPropertyChain: inverse(lod1Solid) ° hasSpatialRelation ° connected ° lod1Solid
```

Analogously, we can define other semantic relations between buildings.

4. CONCLUSIONS

This position paper collected the very first ideas on semantic enrichment of 3D city models. Spatial ontologies are designed to capture concepts, properties, constraints or rules, and relations. Relations can be expressed between instances or between classes (class relations). Relations can have a spatial component, and therefore be spatial or non-spatial. Relations can be not only binary, but also ternary or with a greater cardinality. Current models, such as CityGML, provide a description of concepts and their properties in application domains. CityGML structuring of concepts is mainly based on a hierarchy of parts/subparts. An encouraging approach would be to add spatial constraints and spatio-semantic relations to CityGML, paving the way for the overcoming of ontological impedance.

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