From Quantitative to Qualitative Spaces

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Abstract. Based on previous work, we present our position statement encompassing two mutually complementary topics. The first topic pertains to the ontological grounding of quantitatively specified synthetic environment data. Here, the objective is to generate a qualitative spatial description of a quantitatively modelled (e.g., using primitive geometric features) synthetic environment. The basic aim here is to generate qualitative descriptions of the objects contained in the synthetic environment in terms of spatial relationships pertaining to differing spatial domains. Although the discussion here is grounded in the context of a 'Synthetic Environment Data Representation and Interchange Specification' (SEDRIS), which is primarily used in the (defence) Modelling and Simulation (M&S) domain, the proposed approach is easily extendable to Geographic Information System (GIS) datasets.

Second is the topic of object-level modelling and analysis in next generation dynamic (temporal and event-based) GIS. Here, we propose the macro-level causal analysis of aggregate phenomena in order to serve a high-level qualitative modelling and explanatory function. To establish a context, the modelling of the dynamic spatio-temporal evolution of hot-spots is projected as a potential application domain.

1 Ontological Grounding of Synthetic Environment Data

The need for ontological grounding of real-world or synthetic data that is modelled quantitatively cannot be over-emphasized. Specifically, in so far as the motivations of this work are concerned, the main focus is to generate a qualitative spatial description of a quantitatively modelled (i.e., using primitive geometric features) synthetic environment. Indeed, it is a primary requirement that the desired spatial descriptions consist of qualitative spatial relationships pertaining to differing spatial domains that the objects[1] within the synthetic environment participate in with each other. For a restricted domain, the problem and/or our proposed solution approach may be articulated as follows:

[1] Of course, the notion of an *object* is general enough to allow for primitive types as well as macro-level aggregates and/or clustered entities.

1. how to map an existing synthetic environment data representation model to an ontological TBOX (i.e., the *terminology*) using a well-defined ontology engineering formalism (e.g., OWL)?
2. how to instantiate an ABOX (i.e., the *instances*) based on real synthetic environment data coming from an environment database that is modelled on the externally defined terminology (i.e., the TBOX), and
3. finally (and most importantly), how to map the instance level synthetic environment data to a spatial ontology consisting of a subsumption hierarchy of spatial relationships relevant to distinct spatial domain (e.g., topology, orientation, size, direction). The aim here is to be able to qualitative describe spatial scenes using the generic relationships contained in the spatial ontology.

On the basis of (1-2) above, an object level model of terrain-based quantitative data (e.g., from *polygons* to objects like *buildings* etc) and a high-level ontological view of the synthetic environment database is obtained [Bhatt et al., 2004, 2005]. On the basis of (3), qualitative descriptions of the spatial entities contained within the synthetic environment database can be obtained. Furthermore, since all representation is grounded in a formal ontology description language, which in our case is the OWL-DL fragment of the Web Ontology Language (OWL) [Harmelen and McGuinness, 2004], tools like RACER [Haarslev and Möller, 2003] remain applicable from an ontological reasoning viewpoint. Furthermore, there is also the potential for integrated spatio-terminological reasoning, as formulated in the works of Haarslev et al. [1998], Haarslev and Moller [1997].

Note that although past work, concerning points (1–2), has been based in the context of a 'Synthetic Environment Data Representation and Interchange Specification' (SEDRIS), which is primarily used in the (defence) Modelling and Simulation (M&S) domain, the proposed approach is easily extendable to Geographic Information System (GIS) datasets.[2] Future work concerns the development of point (3), where a qualitative spatial scene description ontology needs to be constructed. In addition to including an elaborate vocabulary for qualitative spatial scene descriptions, we also propose to include physical properties of objects that determine or restrict the spatial relationships that the objects may participate in with each other. For instance, naive distinctions involving strict rigidity (e.g., a solid metal ball), full non-rigidity (e.g., fluids), semi-rigidity (e.g., objects that can be treated as locations) will be included.[3] Furthermore, a special emphasis is to be placed on action-determinant properties (e.g., determining *form* and *function*) of objects that can be used to determine the possible ways in which the object may be manipulated within a dynamic setup. For instance, basic action-determinant questions that such an ontology will answer (for a restricted domain) will include, among other things, whether or not an object can contain other objects, can it deform, it is intrinsically oriented, is it stable, can it be grasped, is it fragile, is it pre-ordained to a specific type of grasp etc. This information in turn will be used in a dynamic spatial

[2] Spatial information modelling in SEDRIS is based on a generic Spatial Reference Model (SRM). WWW: `http://www.sedris.org/`

[3] Albeit not in the form of an explicitly defined ontology, these naive characterisations have already been exploited in the context of modelling dynamic spatial systems [Bhatt, 2008].

re-configuration (planning) process in order to determine the possible ways in which domain objects (for instance, grounded from a synthetic environment database) can be manipulated and also to potentially reduce the state space of possible spatial configurations. Of course, this line of research is being followed keeping in mind certain practical demonstration scenarios rather than a aiming at a completely general solution / ontology.

2 Macro-level Analysis in Dynamic GIS

Modelling and analysis of dynamic geospatial phenomena has emerged as a major research topic within the GIS community. Although present representational and analytical apparatus to examine the dynamics of such phenomena is nascent at best, the issue is increasingly being considered as a major research priority in GIS [Yuan et al., 2004]. Central to the issue of dynamic geospatial phenomena is the integration of time in GIS (Temporal GIS or T-GIS), and dates back at least as far as Hägerstrand's work on the analysis of individual trajectories within 'time geography' [Hägerstrand, 1967]. Indeed, integrating time with GIS is clearly necessary toward the development of GIS capable of monitoring and analysing successive states of spatial entities [Claramunt and Thériault, 1995]. Such capability, necessitating the representation of instances of geographic entities and their change over time rather than change to layers or scenes, is now termed as the future for GIS [Cohn and Hazarika, 2001, pg. 21]. The endeavour is also in line with the approach emphasized in the National Imagery and Mapping Agency's (NIMA) vision for Integrated Information Libraries [NIMA, 2000]. Among other things, NIMA's vision emphasizes the need to arrange information content as objects instead of thematic layers. For instance, Agouris et al. [2000] develops a gazetteer framework that manages representations of geographic entities (based on pattern-matching) and their changes over time rather than changes to layers or scenes. It also facilitates the organisation of geospatial information in an object-oriented manner that captures essential components of the spatio-temporal behaviour of objects. Worboys [2005] regards that an important next step toward the modelling of dynamic geographic phenomena is to move from an object-oriented to an event-oriented view of geospatial changes.

2.1 Causal Analysis of Aggregate or Clustered Phenomena

Most approaches in GIS focus on comparison of temporally-ordered snap-shots, whilst completely ignoring the *causal* (and possibly *teleological*) aspects of the spatial change. A (temporal) GIS should, in addition to accounting for spatial changes, also consider the events behind changes and the facts which enable observation of these changes [Beller, 1991]. In the words of Claramunt and Thériault [1995]:

> '*To respond adequately to scientific needs, a TGIS should explicitly preserve known links between events and their consequences. Observed relationships should be noted (e.g., entities A and B generate entity C) to help scientists develop models that reproduce the dynamics of spatio-temporal processes. Researchers will thus be able to study complex relationships, draw conclusions*

and verify causal links that associate entities through influence and transformation processes'.

Occurrence-driven 'causal explanation' is the process of retrospective analysis by the extraction of an event-based explanatory model from available spatial data (e.g., temporally-ordered snap-shots) [Bhatt, 2008]. Indeed, the explanation is essentially an event-based history of the observed spatial phenomena defined in terms of both domain-independent and domain-dependent occurrences. Causal and, if applicable, telic accounts of a process being modelled are applicable in a diverse range of geospatial phenomena, such as movement of clusters of animals (wild-life biology), monitoring people-clusters in times of crisis on the basis of GPS-based positional information (e.g., emergency and disaster management and planning, defence modelling and simulation) and even in the geospatial analysis of the spread of diseases (epidemiology), where an event-based model can be extracted (or evolution of the phenomena be defined) on the basis of the typology (e.g., *growth*, *shrinkage*, *disappearance*, *merging*, *splitting*, *movement*) of fundamental spatial changes. Additionally, causal analysis is also applicable in real-time surveillance systems where the occurrence criteria for domain-specific events/actions can be defined on the basis of certain, possibly incompletely known, spatial-configurations of the domain objects and/or the patterns of their dynamic evolution – observable spatial changes can be causally linked to known events and actions. Clearly, such a facility necessitates a causal approach encompassing events, actions and their effects toward representing and reasoning about dynamic spatial changes. We hypothesize that a causal representation[4], encompassing occurrences identified by their causes and effects for representing event-driven change is an interesting approach toward accounting for the causal aspects of spatial change. Such an approach will be advantageous in GIS applications concerned with retrospective analysis or diagnosis of observed spatial changes involving either fine-scale object level analysis or macro-level (aggregate) analysis of dynamic geospatial phenomena.

Using the theoretical framework proposed in [Bhatt, 2007, 2008], it is possible to explain spatial phenomena at a higher-level either in terms of domain-specific occurrences that *cause* the observed changes or alternatively, in a domain-independent manner on the basis of the fundamental typology of spatial changes as aforementioned.

The Dynamic Spatio-Temporal Evolution of Hot-spots – Potential Scenario In this context of the causal analysis with aggregate phenomena, we propose to consider a certain class of geospatial phenomena that can be modelled as clusters in space and time. Clusters, popularly known as hot-spots, refer to the aggregation of raw locational data denoting sites of high incidence concentration, with an incidence typically denoting the spatio-temporal location of events [Eck et al., 2005].

We focus on the qualitative modelling and analysis of such spatial clusters (and their spatio-temporal evolution) that are representative of a wide range of geospatial phenomena in disparate domains such as crime analysis, wild-life biology, epidemiology, transportation planning, urban growth analysis and so forth. The main aim is to

[4] Indeed, many different causal formalisations are possible. Our proposal is being promoted in the context of a causal theory as illustrated in [Bhatt, 2007].

formally define a set of domain specific patterns characterising the manner in which certain spatial relationships[5] between different *types* of regions (each *type* denoting a different category of aggregate) evolve over a period of time. Here, the intent is to model behaviour such as *emergence* or *appearance*, *growth* & *shrinkage*, *disappearance*, *spread* and/or *movement*, *stability* etc. Furthermore, it should also be possible to develop (macro) definitions involving the sequential and parallel composition of the behavioural primitives aforementioned, e.g., *emergence* followed by *growth*, *spread* and *stability* or *disappearance* during an observed time-interval. The preliminary report documented in [Bhatt and Whigham, 2006] is an indication of the domain in which this study was first commenced.

[5] Specifically, mereo-topological and directional relationships in 2D geographic space.

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