Towards a contextual representation of landforms

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1 Introduction

Terrain generalisation consists in providing a simplified representation of a terrain adapted to a given purpose. Terrain simplification methods are mostly based on global or local filtering approaches where the emphasis is on performance rather than cartographic generalisation (Jenny et al., 2011). As suggested by Weibel (1992), generalisation should be structure- and purpose-dependent and landforms should be addressable as objects to allow their generalisation. Their generalisation shall then be performed according to the type of landform and their relevance for the map purpose (Guilbert et al., 2014). Hence, landforms shall be classified and described as objects with their own spatial and thematic attributes.

According to Deng (2007), landform classification falls into two groups: on one hand set theory where components are morphometric points (more than often pixels) yielding a segmentation of the terrain and on the other hand category theory where landforms are identified as objects. In a cartographic context, landforms are mainly qualitative objects which are not explicitly portrayed on the map but interpreted by the map reader. The reader will look for salient features on the map that characterise these landforms.

A first step to move towards the automatic classification and generalisation of landforms is to provide a conceptual description of these landforms for there instantiation on the map. However landforms do not correspond to crisp areas of the terrain and the uncertainty of their boundaries is still a modelling issue (Smith and Mark, 2003). Their description cannot be quantitative and may be instead qualitative as they can be represented in multiple ways according to the type of representation, the purpose of the map and user's needs. The problem is often tackled by developing a domain ontology formalising landform definitions but such an ontology would be specific to a given representation. Therefore, we propose a design pattern where the ontology domain is instantiated from a landform prototype and from contextual information.

This paper contributes to multiple representation terrain models by presenting a framework for qualitative description of landforms which can be used for data enrichment (where landforms can be added as objects in the topographic database) and for spatial qualitative reasoning where landforms can be described and represented according to a purpose or a context.

The remaining of the paper is organised in two main parts. Section 2 reviews recent works on qualitative aspects of landform representation, including landform definitions and ontologies. A new conceptual framework is proposed in Section 3. It first lays the foundations of the design pattern, including the landform prototype and second, offers a structure of the domain ontology where landform concepts are built following the design pattern. A last section presents our current works and perspectives.

2 A review of landform representation

2.1 Qualitative description of landforms

As cited by MacMillan and Shary (2009), a landform is broadly defined as "any physical feature of the Earth's surface having a characteristic, recognisable shape". The definition is refined into a geometrical definition, where a landform is "a division of the land surface, at a given scale or spatial resolution, bounded by topographic discontinuities and having (relatively) uniform morphometry"; and into a semantic definition where it is "a terrain unit created by natural processes in such a way that it may be recognised and described in terms of typical attributes where ever it may occur".

Following Strobl (2008), terrain segmentation methods are traditionally data-centric approaches while the object perception is based on semantic-centred concepts with a strong link between visual perception of landforms and natural language. Landforms are usually associated with salient terrain features and not with their boundaries which are not always well-defined. For example, the presence of a mountain is easily associated with the existence of a peak significantly higher than its surroundings but there is no consensual definition of its spatial extent or of the difference between a hill and a mountain.

Semantic concepts describing landforms are usually fuzzy and difficult to conceptualise although the meaning they express is commonly understood by humans (Mark and Smith, 2004). This gap is addressed as the qualitative-quantitative divide. Furthermore, landforms are not perceived in the same way and it is not possible to provide a common set of landforms with universal definitions since the meaning of each term depends on the perception the reader has, which is related to his cultural background, his past experience and the current context (Mark and Smith, 2004).

Indeed, a main difficulty is that, as defined in naive geography (Egenhofer and Mark, 1995), "while many spatial inferences may appear trivial to us, they are extremely difficult to formalise so that they could be implemented on a computer system". Among the different elements of naive geography taken from (Egenhofer and Mark, 1995), some of them require specific attention for the definition of landforms:

- Geographical information is frequently incomplete. People can reason and compensate for missing information. As said above, landforms are perceived from their salient features without a complete spatial description. Landform representation also includes inferences from thematic properties (e.g. geomorphological processes) and implicit knowledge.

- People use multiple conceptualisations of geographical space. These conceptualisations come from differences between perceptual and cognitive spaces. They may relate to a context, e.g. a submarine canyon is not conceived in the same way by a geomorphologist (who sees it as the result of a geomorphological process) and a fisherman (who sees it as a potential fishing area) but also from the scale at which the observation is carried out.

- Geographical space has different levels of detail, these levels can be levels of granularity or levels of scale at which phenomena are represented. Levels of representation are defined by the user's context and the purpose of the representation. Granularity in landforms is expressed in taxonomies yielding general and specialised landforms usually organised in a lattice. For example, the mountain and hill concepts can be defined as two specialisations of an eminence concept.

2.2 Landform ontologies

A solution to address qualitative reasoning and description of landforms is the use of ontologies to provide conceptual definitions that can be tractable by a computer system. Much work focused on domain ontologies characterising specific landforms, for example valleys

(Straumann and Purves, 2011), bays (Feng and Bittner, 2010) and eminences (Sinha and Mark, 2010). They define for each landform geometrical variables that can be measured from a map or a terrain model. However, these variables are specific to each type where a specific context was identified previously and cannot be generalised into a common framework.

National mapping agencies have worked on the development of ontologies describing cartographic objects (Gómez-Pérez et al., 2008). However these ontologies focus on data integration from different sources and do not provide a formal description for reasoning. In the hydrographic domain, Yan et al. (2014) define an ontology of undersea features following the International Hydrographic Organisation terminology (IHO, 2008) according to the framework defined by Fonseca (2001). Its purpose is to allow for the automatic classification of undersea features on nautical charts. It is divided into a domain ontology which describes undersea features from the IHO nomenclature by a series of shape properties and topological relationships, and a representation ontology where features are elements of the chart as portrayed by isobaths and soundings. The set of undersea features is organised into a taxonomy providing descriptions at different levels of granularity.

Yan et al. (2014) explicitly separate the representation from the definition but feature definitions are based on glosses from the IHO with ambiguities from natural language definition and where implicit knowledge is not expressed. Both ontologies are defined for specific contexts and modifying the context requires the definition of new ontologies.

In order to facilitate the development of such ontologies, a structure shall be defined so that ontologies can be generated following a common pattern. Therefore, the objective of this paper is to propose a conceptual framework that helps constructing landform ontologies by defining an ontology design pattern that can be applied according to the context.

3 A framework for landform representation

3.1 Conceptual framework

The proposed conceptual framework is based on the fact that landform definitions depend on the context which includes the user's field of expertise and the purpose of the representation. Therefore, each domain ontology of landforms as observed in the previous section does not provide an absolute description of landforms but a representation associated with a frame of reference within which the description is used.

We propose a framework defined in two parts. First, a design pattern describes the main concepts structuring landforms and the context. Second, the framework of landform ontologies is introduced where concepts are derived from concepts in the design pattern. Elements specifying the context define a frame of reference that characterises the type of representation in a similar approach to map generalisation where map specifications are inferred by user requirements (Balley et al., 2014). The objective of this framework is to move towards a model allowing for the generation of domain ontologies where a lattice of landforms can be instantiated from a frame of reference defined by the user.

3.2 Design pattern

The design pattern describes a solution from which ontologies can be derived. It defines two main concepts which are the *landform prototype* concept, an abstract representation of a landform defining the common structure of all landforms, and the context. As mentioned in the previous section, although landforms are not clearly delineated, they are characterised by salient features which are perceived by people, and hence reveal their existence. For example, a mountain is characterised by its summit while a canyon is located on the map by its course line. We consider that these salient features are intrinsic structural components on which landforms lie and whose definition agrees with the principle of naive geography. Skeletons are mainly points or lines but they can also be more complex structures such as a series of points and lines connecting the summits and ridges of a mountain range and

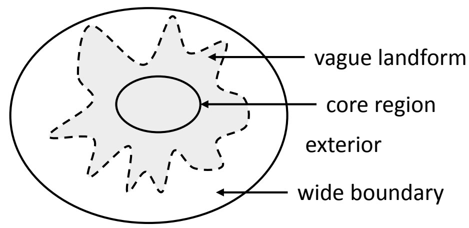

Figure 1: Location of a landform in a regional partition following (Bittner, 1999).

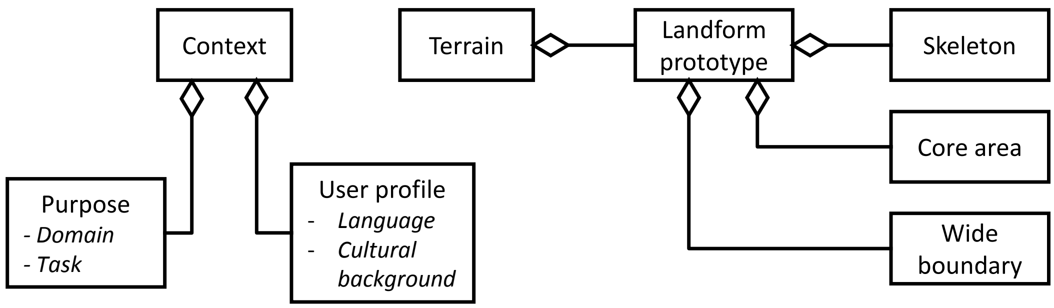

Figure 2: Main concepts in the design pattern.

forming a network. Hence, a landform skeleton is defined as a topological structure which forms the support of a landform.

However, people think mostly about space in terms of regions rather than points and lines (Hobbs et al., 2006). They would not locate the summit or the course line as a point or a line but as regions built around these elements. Hence these salient features are perceived as salient regions built around the landform skeletons. A salient region does not cover the whole landform but only a part. The remaining of the landform belongs to the vague region where the boundary is located. As a way to handle vagueness and indeterminacy of locations, Bittner (1999) located vague objects within a regional partition of three regions: the *core*, the *wide boundary* and the *exterior*. These three regions are used to provide the rough location of a landform (Figure 1). The wide boundary does not correspond to a fuzzy boundary but rather to a region where the boundary is located but whose location is not known.

We define the context of the representation as another concept. The context relates to the purpose of the representation and to the user profile. The purpose of the representation is related to the task the representation is designed for, fixing the domain or the required level of expertise. The user profile shall include the cultural context such as the language or cultural background of the user. The design pattern is summarised in Figure 2.

3.3 Domain ontology framework

The domain ontology is specific to a kind of application and so depends on the context. For example, the terrain is not represented in the same way (with the same focus) on a topographic map and on a nautical chart. Setting the context defines the frame of reference in which the representation is done, providing knowledge on the information content (Lüscher et al., 2007). It includes the different levels of detail (or scale) at which landforms are described. Scale can refer to different terms describing spatial data characteristics. For Dungan et al. (2002), scale includes the resolution of the observation, the grain and the cartographic ratio. Hence, the level of the representation can be defined by a set of

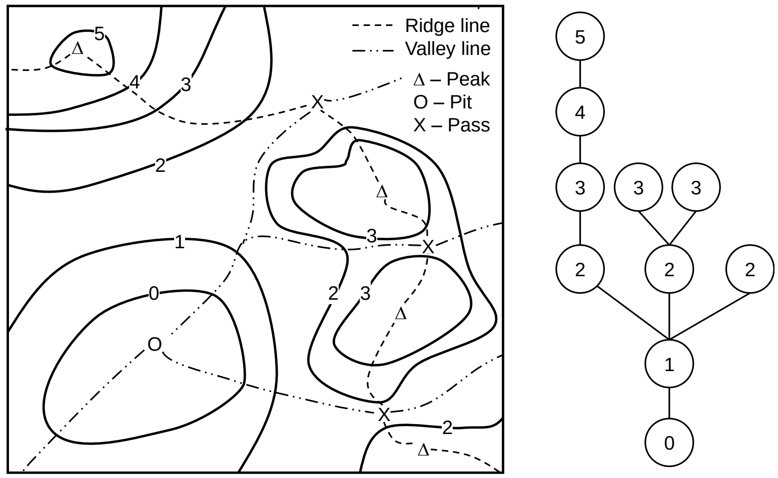

Figure 3: Example of a surface network and its corresponding contour tree.

parameters:

- the resolution at which landforms are observed;
- the cartographic scale of the representation;
- the granularity.

We think that these terms need to be instantiated from the context. The scale of the map is determined by its purpose (e.g. for hiking or for travelling by car). Granularity also relates to the map purpose and depends on the user's level of expertise and on the language used. For example, the term "mountain range" in English can be translated in French by "chaîne de montagne" or by "massif montagneux", which do not convey the same meaning. The different scale terms within the frame of reference shall yield a taxonomy of landforms into a lattice describing the different levels of granularity.

The context may also impose the type of representation (e.g. raster DEM, topographic map) and so, the way landforms are represented including the level of vagueness of the landforms. For example, on a topographic map, a hill can be delineated by only one contour line, having a crisp boundary on the map. In the domain ontology, landforms and their regions are identified from the DTM. Depending on the representation, this DTM can be a raster grid, a TIN or a set of contours and spot heights for example. The skeleton of each landform shall then be extracted from the DTM. Skeletons are topological structures joining critical points and lines of the terrain that shall be extracted from the DTM. The most common topological data structures that fit with the definition of the skeleton are the surface network and the Reeb graph (Guilbert et al., 2014). The surface network is a planar graph formed by the critical points (peaks, pits, saddles) and the critical lines (ridge lines and valley lines) of the terrain (Figure 3). The Reeb graph is the dual of the surface network, but it provides a hierarchical structure of the critical points. The Reeb graph is also topologically equivalent to the contour tree hence such kind of topological structure can be extracted from any kind of DTM representation.

Sinha et al. (2014) provide a surface network ontology where they use descriptive logic to define the ontology concepts. Such an ontology can be adapted to our framework but hierarchical relationships between landforms need to be considered as they affect the classification. For example, a peak can be the summit of two eminences which correspond to two representations at different scales. Equivalent hierarchical data structures based on regions such as the extended Reeb graph (Biasotti et al., 2004) or the feature tree (Guilbert, 2013) can be considered.

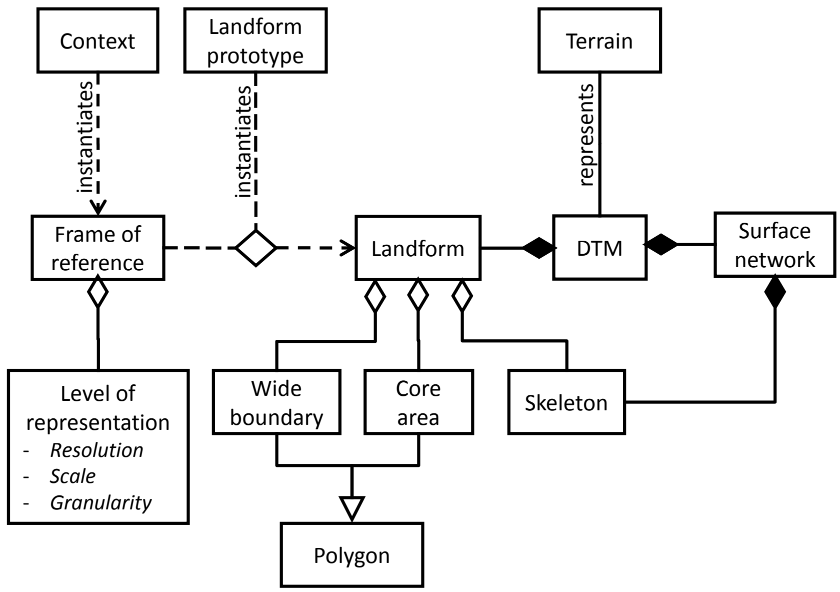

Figure 4: Structure of the domain ontology.

For each kind of landform, the definitions of its core region and wide boundary can be refined since they relate to its shape and complexity. For example, in a valley, the core region can be defined by the valley floor and the wide boundary by the sides of the valley, which fits with the fact that the boundary shall be located on its sides without a precise location (Straumann and Purves, 2011). As another example, the core region of a plateau would be the flat horizontal table while the wide boundary would be defined by the areas corresponding to its steep slopes. However the definition may vary with the representation and the accepted degree of vagueness. Definitions of both regions would be based on some terrain descriptor, contours or some critical lines. In the case of an eminence, one can directly use the valley lines surrounding the summit to define a crisp boundary (which would be a polygonal line) and a core region delineated by these boundaries as in (Sinha et al., 2014). Boundaries can also be defined by a contour line around the summit related to a given level of detail (Guilbert, 2013) or related to a morphometric classification (Chaudhry and Mackaness, 2008).

The structure of the domain ontology is summarised in Figure 4 showing the main concepts. The DTM in the domain ontology is a representation of the terrain. The frame of reference is instantiated from the context and is used to instantiate the landforms from the landform prototype. The core region and wide boundary are polygons on the terrain surface while the skeleton is a component of the surface network.

4 On-going work and perspectives

Landform classification from a terrain model is still a difficult task because of the subjectivity of their definition. Considering that landforms are indeed always described within a given context, this paper proposes an ontology framework for landform representation. Knowledge is structured at two levels. On one hand, concepts describing the context of the representation and the structure of landforms form a design pattern. The main idea is that landforms follow a prototype built upon three components: the skeleton, the core and the wide boundary of the landform. On the other hand, a domain ontology framework is developed where the frame of reference is fixed and the landform concepts are defined with their properties following the design pattern.

On a short term, further work is needed to develop the context and frame of reference concepts. This part can build upon existing work on map requirements and user profile in map generalisation. Further concepts, specifically topological and mereological relationships, may be included to allow spatial qualitative reasoning from the model.

Mechanisms for the instantiation of the domain ontology need also to be explored. As skeleton and areas composing the landforms need to be extracted from the DTM, algorithms generating these elements need to be included in the design pattern.

Currently, visual aspects are not considered. They can be added on a longer term by integrating our framework and a generalisation ontology. It would allow for a more precise description of a user profile and for integrating map requirements in the frame of reference. That could lead to the generation of an application ontology from a task ontology (the generalisation) and one or several domain ontologies (such as the landforms).

The proposed framework may also contribute to facilitating interoperability and data exchange between different domains. Domain ontologies instantiated with this framework shall be structured in the same way, allowing for the development of Web services and Web processes for on-demand mapping.

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