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Review Article

Advances in Geographic Object-Based Image Analysis with ontologies: A review of main contributions and limitations from a remote sensing perspective

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A B S T R A C T

Geographic Object-Based Image Analysis (GEOBIA) represents the most innovative new trend for processing remote sensing images that has appeared during the last decade. However, its application is mainly based on expert knowledge, which consequently highlights important scientific issues with respect to the robustness of the methods applied in GEOBIA. In this paper, we argue that GEOBIA would benefit from another technical enhancement involving knowledge representation techniques such as ontologies. Although the role of ontologies in Geographical Information Sciences (GISciences) is not a new topic, few works have discussed how ontologies, considered from the perspective of a remote sensing specialist, can contribute to advancing remote sensing science. We summarize the main applications of ontologies in GEOBIA, especially for data discovery, automatic image interpretation, data interoperability, workflow management and data publication. Finally, we discuss the major issues related to the construction of ontologies suitable for remote sensing applications and outline long-term future advances that can be expected for the remote sensing community.

1. Introduction

The remote sensing community has evolved rapidly since the launch of the first civilian satellite designed for Earth Observation: Landsat-1 with the Multispectral Spectral Scanner onboard (Castilla and Hay, 2008). The launch of Earth Observation satellites has been accompanied by improved sensors, including multi-spectral, hyper-spectral and radar sensors with increasingly high spatial and temporal resolutions. Additionally, access to the satellite images has been improved by the evolution of web services, and large amounts of data are currently freely provided to the user through various data catalogs held by the principal agencies involved in Earth Observation (e.g., NASA,[1] USGS,[2] INPE,[3] ESA,[4] GEO,[5] AGEOS[6]) and by regional initiatives for data access to developing countries (SEAS-Guyane: https://www.seas-guyane.org/, SEAS-OI, SEAS-Gabon: http://seas-gabon.espace-dev.fr/seasgabon/). Such modern technologies enable researchers to exchange ideas and information more rapidly and easily than was previously possible. Because new and technically improved images are becoming available to a wide community of users, new processing techniques have also been required and implemented in various image processing software applications, either commercial or free. Among the various techniques that have been adopted by the remote sensing community, Geographic Object-Based Image Analysis (GEOBIA) is devoted to developing automated methods to partition remote sensing imagery into meaningful image objects and assessing their characteristics through spatial, spectral and temporal scales, thus generating new geographic information in a GIS-ready format (Hay and Castilla, 2008). Compared with traditional classification approaches, GEOBIA presents at least four new components that are not typically used in pixel-based classification (i.e., the segmentation procedure, the nearest-neighbor classifier, the integration of expert knowledge and feature space optimization) that allow improving the accuracy of remote sensing image classifications (Platt and Rapoza, 2008).

Actually, GEOBIA functions as a link between the pixel world and the vector world and thus has been considered as a sub-discipline of Geographic Information Science (GIScience) (Blaschke, 2010; Hay and Castilla, 2008). During the last decade, the use of GEOBIA has been drastically popularized because of its ability to

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[1] NASA: National Aeronautics and Space Administration (access to data at: http://mirador.gsfc.nasa.gov/).

[2] USGS: United States Geological Survey (access to data at: http://glovis.usgs.gov/).

[3] INPE: Brazilian National Institute for Space Research (access to data at: http://www.dgi.inpe.br/CDSR/).

[4] ESA: European Space Agency (access to data at: http://earth.esa.int/EOLi/EOLi.html).

[5] GEO: Group on Earth Observation (http://www.earthobservations.org).

[6] AGEOS: Agence Gabonaise d'Etudes et d'Observations Spatiales: http://www.ageos.ga/).

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use semantics based on descriptive assessment and knowledge, i.e., the approach incorporates the wisdom of the user (Blaschke and Strobl, 2001). The entire process of image analysis is characterized by the transformation of knowledge (Lang, 2008). Users guide the image processing operation based on their expert knowledge to produce reliable maps. As a consequence of such a success, Blaschke (2010) considers that GEOBIA's recent evolution describes a typical pattern for a new paradigm – or a scientific revolution as mentioned by Hay and Castilla (2008) using the terminology of Kuhn (1962) – for processing remote sensing images.

Although GEOBIA is currently widely adopted, its application highlights important scientific issues which can be summarized as follows (inspired from Comber et al. (2005a)). First, each GEOBIA expert has his own conceptualization of the reality he intends to represent on the image. Indeed, because it is based on expert knowledge, the process transforms object-based image analysis into a type of computer-aided photo-interpretation process in which two experts analyzing the same data will obtain two different results because of their different experiences. Second, the processing chain to achieve a classification is not entirely controlled and documented. For example, GEOBIA includes a segmentation process that is an ill-posed problem (Hay and Castilla, 2008). This step is performed based on parameters among which the choice can be scarcely justified and thus hinders the quality assessment of the classification. The classification step itself is performed in a laborious way at the end of repeated cycles of "trial-and-error" analysis for determining the best features and corresponding thresholds (Durbha et al., 2010; Gao et al., 2011). Third, as a consequence of these two issues (i.e., the analysis based on expert knowledge and the implementation of uncontrolled processing chains), GEOBIA produces methods that are rarely transferable.

Thus, whereas GEOBIA carries significant promise for the efficient processing of remote sensing images,[7] one may wonder how the information on data conceptualization and feature or threshold selection is to be communicated to the remote sensing community, i.e., to the end users and to the scientists interested in the geographic information produced. We argue that GEOBIA needs to be accompanied by technological enhancements that would allow management of the knowledge of GEOBIA specialists, aggregating and sharing such knowledge with the remote sensing community.

Because the future of GEOBIA appears to be an issue of knowledge management, it is likely that knowledge representation techniques can play a pivotal role in the future evolution of remote sensing (El Hajj et al., 2009). Ontologies are widely used in various scientific fields, such as the biological sciences (Bard and Rhee, 2004; Renear and Palmer, 2009), to address data heterogeneity issues by providing solutions for data access, data sharing and data dissemination. Various authors have highlighted the necessity for developing ontologies in Geographic Information Science (GIS) (Agarwal, 2005; Buccella et al., 2009; Couclelis, 2010; Fonseca et al., 2002; Janowicz, 2012; Mark et al., 2005; Visser et al., 2002). However, despite the interest of the GIS community in ontologies, it appears that the remote sensing community still has not appropriated the concepts of ontologies to enable such evolution (in 2012, a search on Web of Science for papers whose titles contained terms such as "ontology" AND "remote sensing" OR "satellite" OR "earth observation" retrieved only nine papers). In fact, few remote sensing experts know how ontologies might benefit their community, possibly because most reviews on the use of ontologies in GIS discuss the issues identified for this area from a standpoint of an artificial intelligence or a GIS expert. Thus, as was questioned in the GIS community a decade ago, the community of remote sensing experts interested in thematic applications (which often describes GEOBIA specialists) might continue to wonder today if using ontologies in remote sensing is merely a buzzword or truly a paradigm shift (Welty, 2003; Winter, 2001).

The objective of this paper is to explain to the GEOBIA community how ontologies could assist them in advancing their research. Because the reader is not expected to be an expert in knowledge representation techniques, ontologies are here considered from the perspective of a remote sensing specialist so that the use of technical details about ontologies is voluntarily restricted. The paper was written in the framework of the EU-FP7-funded project *Biodiversity Multi-Source Monitoring System*: *From Space To Species* (BIO_SOS), focusing on the development of tools and models for consistent multi-annual monitoring of protected areas exposed to human pressures and their surroundings in the various European study areas and elsewhere (www.biosos.eu). In BIO_SOS, we are especially interested in mapping land cover and habitat classes from remote sensing data based on expert knowledge. For this purpose, we use two taxonomies for describing land cover and habitat classes, i.e., the Land Cover Classification System (LCCS) (Di Gregorio et al., 2005) from the Food and Agriculture Organization (FAO) and the General Habitat Category (GHC) (Bunce et al., 2007).

After a brief introduction to the definition of ontologies, we review the main contributions that can be expected from ontologies for the GEOBIA community. We then discuss key research issues to be considered by the remote sensing community to fully benefit from the potential of ontologies.

2. An introduction to ontologies

Because ontologies continue to represent an emerging topic for the remote sensing community, certain important terms may be unfamiliar to the reader. We thus introduce a brief glossary on the key terms related to ontologies mentioned in this paper (Table 1).

2.1. Definition

The definition of the term 'ontology' has been discussed in many previous papers (refer to Agarwal (2005); Couclelis (2010); Mark et al. (2005) for a complete review of the definition of ontologies for GIS applications or to Madin et al. (2008) for ecological applications). A widely accepted definition is the one proposed by Gruber (1993), who defines an ontology as a formal, explicit specification of a shared conceptualization. The conceptualization is an abstract, simplified view of the world that we want to represent for a specific purpose (Gruber, 1993). An ontology intends to identify the concepts and their relationships within a scientific domain. As an example, Fig. 1 introduces a brief conceptualization designed to describe a land cover class called "Broadleaved Evergreen High Trees" as defined in the Land Cover Classification System.

As mentioned in the definition, such a conceptualization needs to be explicit, shared and formal to be considered an ontology. Here, explicit means that concepts and constraints are precisely defined (e.g., in Fig. 1, the concept of 'High' refers to a height of more than 14 m). A shared conceptualization means that the ontology captures consensual knowledge. In our example, concepts are derived from a widely used taxonomy, i.e., the Land Cover Classification System. Finally, a formal conceptualization means that the ontology is machine understandable. When these three qualities are met, the conceptualization can be implemented in dedicated software (e.g., Protégé: protege.stanford.edu) that allows exploiting all of the potentialities of ontologies.

[7] GEOBIA is widely used for urban studies (Durieux et al., 2008) and habitat mapping (Lucas et al., 2007) but see the complete review of potential applications of GEOBIA on remote sensing images proposed by (Blaschke, 2010).