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Temporal logic and operation relations based knowledge representation for land cover change web services

Jun Chen [a,d], Hao Wu [a,b,*], Songnian Li [c,d], Anping Liao [a], Chaoying He [a], Shu Peng [a]

[a] National Geomatics Center of China, Beijing 100830, China
[b] School of Remote Sensing and Information Engineering, Wuhan University, Wuhan, Hubei 430079, China
[c] Department of Civil Engineering, Ryerson University, Toronto, Ontario, Canada M5B 2K3
[d] School of Environment Science and Spatial Informatics, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China

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ABSTRACT

Providing land cover spatio-temporal information and geo-computing through web service is a new challenge for supporting global change research, earth system simulation and many other societal benefit areas. This requires an integrated knowledge representation and web implementation of static land cover and change information, as well as the related operations for geo-computing. The temporal logic relations among land cover snapshots and increments were examined with a matrix-based three-step analysis. Twelve temporal logic relations were identified and five basic spatial operations were formalized with set operators, which were all used to develop algorithms for deriving implicit change information. A knowledge representation for land cover change information was then developed based on these temporal logic and operation relations. A prototype web-service system was further implemented based on OWL-DL. Both online access and conversion of land cover spatio-temporal information can be facilitated with such a web service system.

1. Introduction

Land cover information is widely used in scientific research, socio-economic development and many other areas (Foley et al., 2005; Running, 2008; ICSU, 2010; Rodriguez-Galiano et al., 2012). It has been identified recently by the Group of Earth Observation (GEO) Task US-09-01a as the fifth highest-ranked observation and common to the nine societal benefit areas (SBAs) of GEO (Friedl, 2010). Since 1990, tremendous efforts have been devoted to the global land cover mapping by international communities and six types of global land cover maps have been derived from space-borne remotely sensed data at coarse resolutions (1 km or 300 m) (Hansen et al., 2002; Herold et al., 2008; Friedl et al., 2010). China started to produce more precise global land cover products at 30 m resolution by integrating Landsat TM and other remote sensing images (Chen et al., 2011; Gong et al., 2013). With all these global land cover datasets, several websites have been developed to provide web-based land cover information services to researchers and the public, such as the United States Geological Survey (http://www.mrlc.gov), the University of Maryland (http://glcf.umiacs.umd.edu/data/landcover), the National Geomatics Center of China (NGCC) (http://www.globallandcover.com), etc. These websites, among other similar service sites, are limited to providing static information and cannot provide land cover change (LCC) information, such as where land cover changes have occurred and what types of changes are (Parker et al., 2003; Olofssona et al., 2012). Therefore, the development and application of a web-based LCC information service are becoming a priority of remote sensing and land cover communities, and have been listed under one of the sub-tasks of GEO for the period of 2012 to 2015 (see http://www.earthobservations.org/ts.php?id=155 for more information).

The spatial distribution and attributes of land cover may change over time and the resulted LCC can be represented in the form of a sequence of snapshots and/or increments (Turner et al., 1995; Nunes and Auge, 1999; Lambin et al., 2003; Xian et al., 2009). The integration of these land cover snapshots, increments, remote sensing imagery and sample datasets is one of the fundamental tasks for the development of web-based LCC information services. A number of spatio-temporal relations and computational relations exist among these LCC information ingredients, and need to be described, capsulized and published as part of web-based services. In fact, these relations will facilitate the intelligent extraction or dynamic computation of some implicit information hidden within the snapshots, increments and other datasets.

Spatio-temporal relation and data modelling is a hot research topic during the last 20 years and a number of methods and algo-

* Corresponding author at: National Geomatics Center of China, Beijing 100830, China.
E-mail addresses: chenjun@nsdi.gov.cn (J. Chen), whgis@yahoo.cn (H. Wu), snli@ryerson.ca (S. Li).

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rithms have been developed (Chen and Jiang, 2000; Artale et al., 2001; Pierre and Smith, 2004; Noy and Rector, 2006; Gutierrez et al., 2007; Tappolet and Bernstein, 2009). The spatio-temporal relations of LCC ingredients and their knowledge representation, however, have not been sufficiently elaborated yet (Song et al., 2009; Fritz et al., 2012). There are some interesting developments from computer sciences in temporal relation modelling and knowledge representation. For instance, Welty and Fikes (2006) proposed a 4D-fluent model to describe the qualitative state transition of temporal objects using the temporal relations among time-slices and time-intervals. With the representation of the domain temporal knowledge, the temporal reasoning about the state transition was realized. This approach has since been used by several people in their semantic web studies, especially for extraction of implicit information and service composition of web services (Milea et al., 2008; Batsakis and Euripides, 2010). However, only temporal objects and relations were dealt with in their studies without considering spatial components as well as spatio-temporal relations. On the other hands, the operation relations among algorithms and models have also been formulated for the development of the web-based geo-processing services in both computer science and remote sensing fields (Di, 2004; Chen et al., 2009). Current works focus mainly on the simple remotely sensed image processing, and the operation relations of LCC have not been investigated.

Following the above discussion, this paper examines the temporal and operation relations among land cover snapshots and increments, and proposes a knowledge representation for LCC services using both temporal logic and operation relations. The remainder of this paper is organized as follows. A matrix arithmetic approach is used to analyse the temporal relations among snapshots and increments in Section 2 and twelve possible temporal logics are derived. Section 3 defines five basic operation relations among LCC snapshots and increments using set operators. The knowledge representation for LCC web services is discussed in Section 4 and a spatio-temporal conversion based on knowledge representation is proposed by utilizing the discussed temporal logic and operation relations. Section 5 presents the experiments of a prototype LCC web service with the methods proposed in this paper. Finally, some conclusions and future research directions are discussed in Section 6.

2. Temporal logic analysis among snapshots and increments

Time-interval and time-slice are two types of temporal objects in temporal data modelling (ISO, 2002). While the former refers to a line segment in time space with a starting point, an ending point and a length attribute, and the later represents one point in time space. The temporal logic proposed by Allen (1983) is suitable for the representation of the logic relations among time-intervals, but not for the relations between two time-slices or relations between a time-slice and a time-interval. Since a land cover snapshot and an increment can be considered as a time-slice and a time-interval, respectively, Allen's temporal logic can be applied directly to represent the logical relations between two increments, but needs to be extended for the representation of logic relations between two snapshots or a snapshot with an increment.

Suppose that $S(t)$ represents a time-slice at time t, and $I(t_s, t_e)$ represents a time-interval with t_s and t_e as its starting and ending time, as shown in Fig. 1. $S_1(t_1)$, $S_2(t_2)$, $S_i(t_i)$ are time-slices at time t_1, t_2 and t_i, respectively, and $I_1(t_{1s}, t_{1e})$, $I_2(t_{2s}, t_{2e})$ and $I_j(t_{js}, t_{je})$ are time-intervals t_{1s} to t_{1e}, t_{2s} to t_{2e}, and t_{js} to t_{je}, respectively.

2.1. Definition of temporal relations between two time-slices

The temporal relations between $S_1(t_1)$ and $S_2(t_2)$ may have three cases: $t_1 > t_2$, $t_1 = t_2$, or $t_1 < t_2$. This means that $S_1(t_1)$, and $S_2(t_2)$ have three types of temporal relations *Before*, *Equals* and *After*. In order to conduct a quantitative analysis, they are represented as a temporal relational vector V(S_1, S_2) = {*Before*, *Equals*, *After*}. If we use A1, A2, A3 to represent *Before*, *Equals* and *After*, the temporal relational vector A can be further simplified as A = {A_1, A_2, A_3} (see Fig. 2).

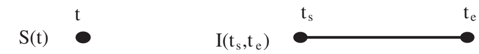

Fig. 1. Time-slice and time-interval.

2.2. Derivation of temporal relations between time-slice and time-interval

The temporal relations between $S_i(t_i)$ and $I_j(t_{js}, t_{te})$ can be derived by separate comparison of t_i with t_{js} and t_i with t_{je}, respectively. They may be calculated by $R(S_i, I_j) = R(S_i, S_{js}) \times R(S_i, S_{je})$. If we use temporal relational vectors $A_s(A_{s1}, A_{s2}, A_{s3})$ and $A_e(A_{e1}, A_{e2}, A_{e3})$ to represent $R(S_i, S_{js})$ and $R(S_i, S_{je})$, respectively, a temporal relational matrix between s_i and I_j can be given as follows:

$$R(S_i, I_j) = \begin{pmatrix} A_{s1} \\ A_{s2} \\ A_{s3} \end{pmatrix} (\mathrm{A}_{e1} \quad \mathrm{A}_{e2} \quad \mathrm{A}_{e3}) = \begin{pmatrix} A_{s1}A_{e1} & A_{s1}A_{e2} & A_{s1}A_{e3} \\ A_{s2}A_{e1} & A_{s2}A_{e2} & A_{s2}A_{e3} \\ A_{s3}A_{e1} & A_{s3}A_{e2} & A_{s3}A_{e3} \end{pmatrix} \quad (1)$$

Each element of the above matrix will either be a true logic relation or take an empty value. This is determined by analyzing the relative temporal position of t_i with t_{js} and t_{je}, respectively, along the time line, as shown in Fig. 3. Let us take $A_{s1}A_{e1}$ as an example (see Table. 1), where A_{s1} and A_{e1} both refer to *Before*. For a time-slice S_i, its time t_i is before the starting time and ending time of I_j, i.e., we have $t_i < t_{js}$ and $t_i < t_{je}$. Therefore, $A_{s1}A_{e1}$ takes *Before* as its temporal logic value. Another example is $A_{s1}A_{e3}$, where A_{e3} represents *After*. It is not possible to have $t_i < t_{js}$ and also $t_i > t_{je}$. Therefore, $A_{s1}A_{e3}$ should take an empty value $\varnothing$.

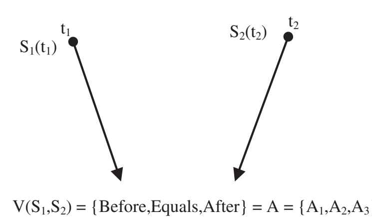

Fig. 2. Temporal relations between two time-slices.

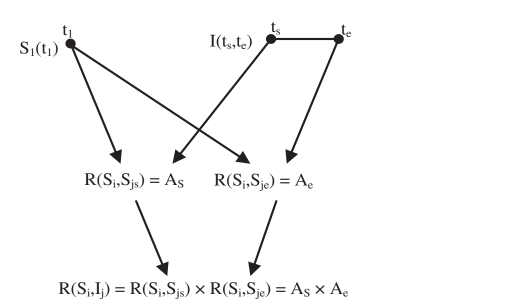

Fig. 3. The process of computing temporal relations between a time-slice and a time-interval.