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Introduction

"Man must rise above the Earth, to the top of the atmosphere and beyond, for only thus will he fully understand the world in which he lives" said Socrates more than twenty four hundred years ago. Eventually we got there, and looking down we quickly realized the potential of such a viewpoint in identifying and analyzing natural phenomena, and the effect of human activity over the surface of the Earth.

From a general perspective, remote sensing is the science of acquiring and analyzing information about objects or phenomena from a distance. From the Earth's observation stand point, its ultimate goal is to describe or quantify surface patterns in order to contribute to the understanding of the underlying processes (Blaschke and Strobl, 2001).

In the past few decades remote sensing technology has advanced from predominantly military uses to a variety of urban and environmental applications; from photographic systems to sensors that convert energy from most of the electromagnetic spectrum to digitally recorded electronic signals; from aircraft to satellite platforms.

Currently a growing number of aerial and orbital remote sensing systems[1], operated by governmental institutions and private companies, is continuously delivering data of distinct characteristics – in varying spatial resolutions, including optical and multispectral, SAR[2] and LIDAR[3] systems – enabling a diverse set of applications, such as environmental management and monitoring, land use and land cover mapping, urban planning, agricultural inventorying, disaster management, etc.

Remote sensing data, whose acquisition and handling was once a privilege of scientists and the military, is now available to virtually any one. In this respect,

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[1] According to (ITC, 2009) 18 earth observation satellites were put in orbit in 2008, and 24 are scheduled for 2009.
[2] Synthetic aperture radar.
[3] Light Detection and Ranging.

bringing up a Brazilian initiative, it is worth mentioning that the CBERS[4] imagery is distributed free-of-charge in electronic format for users in any part of the world (Epiphanio, 2008).

If in one hand the growing availability of remote sensing data provides very useful information for dealing with the current rate of human activity and environmental change, on the other, it presents policy and decision makers with an overwhelming amount of data to contend with. The ability to detect, monitor and properly manage this change and its implications requires tools that can efficiently transform this mass of multisource and multitemporal geospatial data into actionable information.

Currently, however, the majority of techniques for the analysis of remote sensing imagery requires intense human intervention. Most land cover maps, for instance, are created solely by means of visual interpretation. Remote sensing image analysis is generally a slow and subjective process, strongly dependant on specialized personnel (Rego, 2003). Considering, additionally, the geographic extension of the regions of interest, specially in large countries like Brazil, and the required temporal frequency for the effective monitoring and management of urban and environmental phenomena – the size and complexity of the tasks at hand represent an unquestionable demand for the development of robust computational techniques for information extraction and interpretation of remote sensing data (Carrion et al., 2002).

But even after a few decades of research on the fields of computer vision and photogrametry, fully automatic remote sensing image interpretation systems do not seem realistic in foreseeable future (Heipke, 2005). Much effort, however, has been put in the direction of enhancing the degree of automation and decreasing the subjectivity in the interpretation of such images.

Traditionally, image interpretation has been treated as a pattern recognition problem. In (Jain et al., 2000) pattern recognition techniques are grouped in categories. Three of them are particularly important for the analysis of remote sensing data: statistical methods; methods based in machine learning; and structural methods.

[4] China-Brazil Earth-Resources Satellite.

Statistical methods (Webb, 2002) can be regarded as the conventional solution in terms of remote sensing. In this category, object classes are represented by probability density functions defined over a predetermined attribute space. These functions subdivide the attribute space in regions that contain the patterns associated to each class. Appropriately modeling probability densities is the main challenge of this type of approach. Limitations as to the number of the available training patterns usually imply in the adoption of simple models, and in poor classification performance.

Methods based on machine learning (Li et al., 2000; Mciver et al., 2001; Zhong et al., 2008; Chi e Ersoy, 2005), are directed towards the learning of complex relations among sample patterns, even in the absence of explicit models. The main disadvantage of these methods is their high demand for training samples, what excludes them as an alternative for many remote sensing applications.

Structural methods involve complex patterns. They usually adopt a hierarchical approach in which descriptions of the patterns are based on simpler patterns recursively, until primitive patterns are reached. Particularly relevant in this context are the so-called knowledge-based or cognitive systems (Liedtke et al., 1997; Bückner et al., 2001; Schiewe et al., 2001; Centeno et al., 2003). The main focus of those systems is the modeling of the classes of objects expected to be found in an image through the explicit representation of prior knowledge about their spectral, morphological or topological characteristics. Such knowledge, acquired from a human specialist, can reduce significantly the demand for training patterns.

There are several other advantages of embodying image understanding knowledge into explicit structures (Crevier and Lapage, 1997). First, knowledge can be easily added to a knowledge base, without modifying preexisting rules. When laid out explicitly, knowledge can be more easily validated, since contradictions and omissions become apparent. Knowledge structures also favor interactive problem solution, providing a way to explore alternative means of extracting information from images. And last but not least, explicit represented knowledge provides for easier collaboration, for knowledge interchange among those tackling similar problems.

In addition to contextual or structural knowledge, temporal knowledge – regarding the temporal dynamics or possible changes in landscape objects – can be of great value in the interpretation process (Melgani et al., 2003), as the contemplation of data from the same region taken at different points in time enables change detection and monitoring of a large set of phenomena (Krug, 1999).

Most of the (semi) automatic methods proposed thus far can be regarded as "post-classification" approaches. These methods are based on separate single-date classifications whose results are subsequently compared (Weismiller et al., 1977). More powerful alternatives, called "cascade-classification" approaches (Swain, 1978), use all the information contained in the image sequence, trying to exploit the temporal correlation between images.

A number of cascade classification schemes have been proposed, including Bayesian methods (Serpico and Melgani, 2000), neural networks (Melgani et al., 2003; Bruzzone et al., 1999), as well as multi classifier approaches (e.g. Bruzzone et al., 2004). Regardless of the increasing interest in classification systems based on fuzzy logic, fuzzy cascade multitemporal methods are mentioned infrequently in the literature compared to other approaches. In (Mota et al., 2007), a fuzzy multitemporal classification method is proposed for land-cover updating applications, the method is though restricted to applications where the correct class of the object being classified at an earlier time is known.

This research aims at responding to the demand for efficient and versatile remote sensing image interpretation techniques. The computational methods presented in this PhD Thesis are devised to support a large spectrum of applications, making it possible to integrate multitemporal data generated by different sensors and to explore explicitly represented knowledge in the interpretation process. They represent an open-source development initiative, thus providing concrete means for further research and for their application.

In this work both a multitemporal, cascade-classification method based on fuzzy Markov chains, and a knowledge-based multitemporal framework for the interpretation of remote sensing data are proposed. As a way to validate the framework some alternative variations of the fuzzy Markov chain classification method were implemented using its functionalities. The framework, nevertheless, was designed to permit the implementation of diverse multitemporal knowledge-based methods.

The proposed framework is actually an extension of the previously existing InterIMAGE framework (Costa et al., 2008), whose interpretation engine is based on the GeoAIDA knowledge-based, remote sensing image interpretation system (Pahl, 2003; Pahl, 2008). GeoAIDA's core has been modified with the inclusion of explicit temporal knowledge representation and processing capabilities.

The proposed multitemporal, cascade-classification method extends what was proposed in (Mota et al. 2007) and introduces a new fuzzy Markov chain multitemporal technique that overcomes the aforementioned limitation of the earlier method. The main innovation of this new approach is the option of using object features other than the correct, complete classification as the information from the earlier epoch. Moreover, a definition of class transition possibility is introduced and its relationship to the concept of class transition probability is elucidated. Still regarding (Mota et al. 2007), a novel analytic technique for the estimation of transition possibilities is proposed.

Experiments were conducted on a sequence of three LANDSAT images from the central region of Brazil. The results have indicated that the proposed multitemporal scheme may significantly improve classification accuracy as its monotemporal counterpart, as long as there is a correlation between the data sets from the dates being considered.

Part of the results reported in this Thesis have been anticipated in the article "Cascade multitemporal classification based on fuzzy Markov chains" (Feitosa et al., 2008), published in the ISPRS Journal of Photogrammetry and Remote Sensing. The fuzzy Markov chain model for multitemporal classification is presented in that work, but in a more restricted formulation, in the sense that it is subsumed by the model proposed here. Additionally, the article "InterIMAGE: uma plataforma cognitiva open-source para a interpretação automática de imagens digitais" (Costa et al., 2008), published in the Revista Brasileira de Cartografia (RBC), presents a resumed description of the InterIMAGE framework, but still with no multitemporal functionalities.

This research has been developed in the context of an international scientific cooperation project called M4, in which take part PUC-Rio, UERJ, Embrapa and the Leibniz Hannover University. The Project is supported by the PROBRAL initiative, founded by CAPES and the DAAD. Part of the research has been developed at the Leibniz Hannover University, within an internship student program founded by CAPES (*Bolsa Sanduiche*). Furthermore, the research has also contributed to the InterIMAGE Project, a scientific innovation project that aims at the development of an open-source remote sensing data interpretation environment, leaded by the Computer Vision Lab of the Electrical Engineering Department of PUC-Rio and by the Brazilian National Institute for Space Research (INPE).

1.1. Objectives of the thesis

The general objective of this research project is the development of knowledge-based computational techniques to support the interpretation of *multitemporal* remote sensing data. Its main focus is on the investigation of *temporal knowledge*, i.e. knowledge about the temporal dynamics of the classes of objects relevant for a particular application, and, more specifically, on the incorporation of such knowledge in a knowledge-driven interpretation process.

This work investigates the explicit representation of temporal knowledge and its integration with other types of knowledge, and also, the processing and automatic acquisition of temporal knowledge.

Considering the general objective stated above, the work reported in this Thesis has concentrated on two main, interrelated, specific objectives. The first is the development of a novel multitemporal classification method that provides for the automatic estimation of its parameters – which can be regarded as temporal knowledge – and for the exploration of such knowledge in the classification process. The second specific objective can be posed as the design and implementation of a knowledge-based framework for multitemporal interpretation of remote sensing image data.

As a way to validate the classification method, which is structured through the concept of fuzzy Markov chains, experiments were designed aiming at the classification of three LANDSAT images from different years of an area in the central region of Brazil. And as a way to validate the proposed Framework, which is an extension of a previously existing knowledge-based image interpretation framework – InterIMAGE (Costa et al., 2008; Oliveira et al. 2008), which is in turn based on the GeoAIDA system (Pahl, 2003, 2008); different variants of the novel multitemporal method were implemented onto the extended framework.

In summary, the novel scientific contributions of this thesis are:

(1) The multitemporal extension of the InterIMAGE knowledge-based framework for the interpretation of remote sensing image data – with the introduction of functionalities for the representation and processing of explicit temporal knowledge.

(2) A novel, cascade-classification method for the classification of multitemporal remote sensing images, based on the concept of fuzzy Markov chains.

(3) A novel analytical method for the estimation of the multitemporal model parameters.

1.2. Organization of the remainder of the thesis

The next chapter describes the state of the art in the areas of knowledge-based image interpretation, and of multitemporal methods for the interpretation of remote sensing image data.

Chapter 3 describes the proposed multitemporal cascade-classification method and Chapter 4 presents the results of an application of the method over a set of LANDSAT images.

Chapter 5 presents the design of the proposed multitemporal knowledge-based, image interpretation framework, beginning with a review of the knowledge representation and control mechanism implemented in GeoAIDA.

Chapter 6 presents the results of experiments designed to validate the multitemporal framework, through the implementation of the multitemporal cascade-classification method described in Chapter 3.

Chapter 7 presents the final conclusions and directions for further development of what is presented in this Thesis.