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Hierarchical extraction of landslides from multiresolution remotely sensed optical images

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ABSTRACT

The automated detection and mapping of landslides from Very High Resolution (VHR) images present several challenges related to the heterogeneity of landslide sizes, shapes and soil surface characteristics. However, a common geomorphological characteristic of landslides is to be organized with a series of embedded and scaled features. These properties motivated the use of a multiresolution image analysis approach for their detection. In this work, we propose a hybrid segmentation/classification region-based method, devoted to this specific issue. The method, which uses images of the same area at various spatial resolutions (Medium to Very High Resolution), relies on a recently introduced top-down hierarchical framework. In the specific context of landslide analysis, two main novelties are introduced to enrich this framework. The first novelty consists of using non-spectral information, obtained from Digital Terrain Model (DTM), as *a priori* knowledge for the guidance of the segmentation/classification process. The second novelty consists of using a new domain adaptation strategy, that allows to reduce the expert's interaction when handling large image datasets. Experiments performed on satellite images acquired over terrains affected by landslides demonstrate the efficiency of the proposed method with different hierarchical levels of detail addressing various operational needs.

1. Introduction

1.1. Context

In the field of Earth observation, a new generation of sensors with meter and sub-meter resolution has led to an increased production of Very High Resolution (VHR) optical images (Benediktsson et al., 2012), and to improved operational capabilities for monitoring geohazards. Especially, several studies demonstrated that such kind of imagery enables to inventory and delineate landslide-affected areas (Nichol and Wong, 2005; Barlow et al., 2006; Martha et al., 2010; Mondini et al., 2011; Stumpf and Kerle, 2011), providing valuable information for the estimation of potential risks to infrastructures and human lives. Comprehensive landslide inventory maps should ideally also provide information about the respective sub-parts of each single landslide which are often characterized by different kinematic patterns. Such type of spatial information on landslide sub-units is of paramount importance for quantitative hazard assessments (Thiery et al., 2007) and the identification of landslide that are more prone to imminent acceleration or fluidization (Raucoules et al., 2013). VHR satellite images contain sufficient spatial details to depict small geomorphological surface features such as faults, scarps, fissures, rock blocks and lobes, and should in principle also enable an analysis at the level of sub-parts composing a landslide. However, established concepts of landslide geomorphology, such as a first order differentiation between source area, transport area and toe (Fig. 1), do not directly correspond to spectrally homogeneous pixels or regions in VHR images. Indeed, the different sub-parts appear heterogeneous as they generally contain different kinds of basic elements with a specific spatial organization (e.g., different kinds of fissures, different sizes and shapes of rock blocks, etc.). Consequently, by opposition to lower resolution images (Yilmaz, 2009; Kayastha et al., 2013), landslides can be considered as hierarchies of complex patterns

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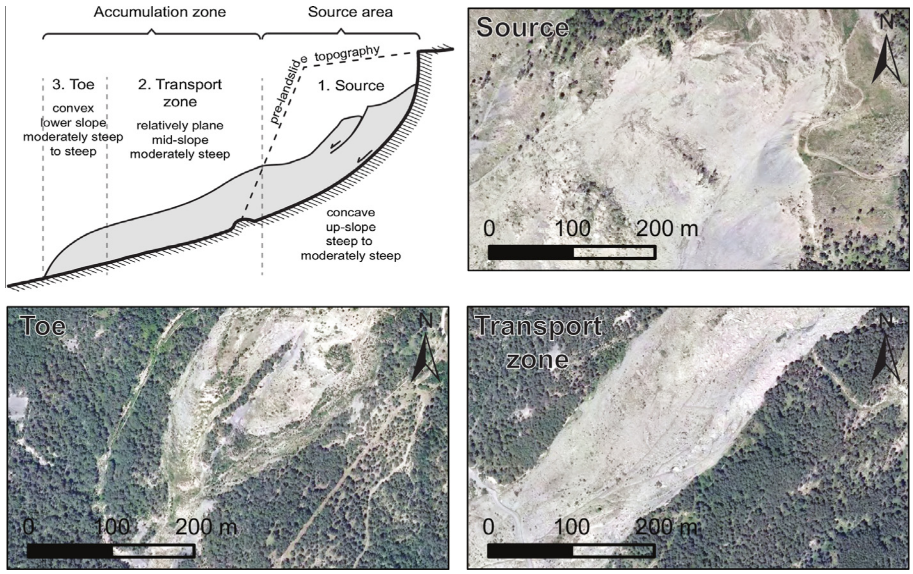

Fig. 1. Schematic partition of a landslide into sub-units (source area, transport area and toe) and their typical geomorphological features. The image depicts the distinguished sub-units on an aerial photograph (50 cm, © IGN, 2008) and shows the heterogeneous surfaces including deformation features such as fissures and different sizes of rock blocks. This example illustrates that geomorphological definitions do not correspond directly to spectrally homogeneous areas depicted in the remote sensing images.

composed by sub-objects of interest. One may notice that the conceptual model in Fig. 1 allows us to identify potentially useful features (e.g., slope gradient, slope curvature, differences in altitude) to distinguish the different landslide sub-parts.

Due to the expanding fleet of VHR optical satellites such as the French PLEIADES constellation (de Lussy et al., 2005), the challenges associated with VHR images are gaining increasingly greater importance in the context of landslide mapping (Guzzetti et al., 2012). On the one hand, the size and the complexity of the images make the visual analysis a time consuming and error prone task (Galli et al., 2008; Fiorucci et al., 2011). On the other hand, state-of-the-art image analysis tools, which are usually considered for the mapping of landslides from lower resolution images, rely on radiometric homogeneous hypotheses of the landslides represented in the images. Consequently, these tools cannot handle the new levels of spatial details provided by VHR images (Blaschke, 2010). Therefore, new image analysis methodologies have to be proposed for the hierarchical mapping of landslides from VHR optical satellite images.

1.2. Related works

In this context, various region-based approaches have been proposed to automate the extraction of landslides from VHR images (Barlow et al., 2006; Martha et al., 2012; Lu et al., 2011; Stumpf and Kerle, 2011; Lahousse et al., 2011; Hölbling et al., 2012; Stumpf et al., in press). In opposition to pixel-based approaches that mainly use spectral and textural information (Townshend et al., 2000; Mallinis et al., 2008), region-based approaches enable to consider high-level (e.g., contextual, geometrical) features to describe the objects to be classified. Indeed, region-based approaches enable to transfer high-level knowledge in computer-accessible features leading to discriminatory decision sets. Such decision sets have been employed for the mapping of landslides from HR (Martha and Kumar, 2013) and multitemporal VHR images (Lu et al., 2011). Stumpf et al. (in press) have also proposed a supervised framework to automatically select discriminative features among a multitude of potentially useful ones. Nevertheless, most of the proposed approaches do not consider the hierarchical organization of the objects of interest (Benz et al., 2004), that is a serious drawback when dealing with VHR optical satellite images.

To tackle this issue, two key-concepts can be considered: using multiple images, and using multiple spatial resolutions. On the one hand, multiple images provide complementary information, that can enrich each other. This is specifically true in the case where such images gather different radiometric values, that then carry various semantic information. On the other hand, using images at multiple spatial resolutions provides hierarchical links between their respective radiometric information. (In particular, the availability of a large range of spatial resolutions, from Medium Spatial Resolution (MR, 30-5 m) to VHR images, has already led to methods for the extraction of hierarchical patterns (Akcay and Aksoy, 2008; Wemmert et al., 2009; Gaetano et al., 2009).) These considerations motivate our use of multiple images at multiple spatial resolutions (Chang et al., 2007). In particular, we propose to take advantage of this potential spatial (Sun et al., 2003) and radiometric enrichment to propose a multiresolution representation of the data, leading to a hierarchical unsupervised region-based approach.

1.3. Contributions

Based on these considerations, a top-down hierarchical region-based framework has been recently proposed by Kurtz et al. (2012) to segment and classify multiresolution images from the lowest to the highest resolution, and then finally extract complex patterns from VHR images. This top-down hierarchical approach (TDHA) constitutes a generic and versatile framework. In this work, we propose to adapt and improve it, in order to efficiently deal with the case of landslide mapping from remote sensing imagery.

From a methodological point of view, our contributions are twofold. Firstly, we propose to integrate topographic and morphometric *a priori* knowledge derived from non-spectral data, namely Digital Terrain Model (DTM), for guiding the segmentation/classification process. This strategy has shown promising results in the context of mapping shallow landslides with pixel-based approaches (Mondini et al., in press). In our approach, this knowledge is used for the construction of the hierarchical image representation data structure, namely a binary partition tree (BPT) (Salembier and Garrido, 2000) considered for the segmentation. It is also used to enrich the feature space in the context of a multiresolution classification procedure (Kurtz et al., 2010). This enriched TDHA is described in Subsection 2.1. Secondly, we propose a new strategy that