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Unsupervised change detection in VHR remote sensing imagery – an object-based clustering approach in a dynamic urban environment

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ABSTRACT

Monitoring of changes is one of the most important inherent capabilities of remote sensing. The steadily increasing amount of available very-high resolution (VHR) remote sensing imagery requires highly automatic methods and thus, largely unsupervised concepts for change detection. In addition, new procedures that address this challenge should be capable of handling remote sensing data acquired by different sensors. Thereby, especially in rapidly changing complex urban environments, the high level of detail present in VHR data indicates the deployment of object-based concepts for change detection. This paper presents a novel object-based approach for unsupervised change detection with focus on individual buildings. First, a principal component analysis together with a unique procedure for determination of the number of relevant principal components is performed as a predecessor for change detection. Second, k-means clustering is applied for discrimination of changed and unchanged buildings. In this manner, several groups of object-based difference features that can be derived from multi-temporal VHR data are evaluated regarding their discriminative properties for change detection. In addition, the influence of deviating viewing geometries when using VHR data acquired by different sensors is quantified. Overall, the proposed workflow returned viable results in the order of κ statistics of 0.8–0.9 and beyond for different groups of features, which demonstrates its suitability for unsupervised change detection in dynamic urban environments. With respect to imagery from different sensors, deviating viewing geometries were found to deteriorate the change detection result only slightly in the order of up to 0.04 according to κ statistics, which underlines the robustness of the proposed approach.

1. Introduction

The broader availability of very-high resolution (VHR) remote sensing imagery, especially in the temporal domain, requires new concepts for change detection (Bruzzone and Bovolo, 2013). Besides very-high resolution aerial and SAR imagery, spaceborne optical VHR images with spatial resolution of 1 m or less are acquired by satellite systems such as IKONOS, QuickBird, GeoEye, WorldView or Pléiades. After around 15 years of VHR data collection by these systems, the analysis of huge amounts of data necessitates highly automated unsupervised methods for change detection (Bruzzone and Bovolo, 2013; Hussain et al., 2013). Regarding rather traditional medium (e.g., MODIS, AVHRR) and high resolution (e.g., Landsat, SPOT) sensors, a broad range of efficient, mostly pixel-based methods for change detection exist (Coppin et al., 2004; Lu et al., 2004; Singh, 1989). Due to the high level of detail present in VHR imagery, change detection becomes more complex and traditional (pixel-based) methods are considered less effective (Bruzzone and Bovolo, 2013; Hussain et al., 2013). This becomes even more crucial in urban environments where heterogeneous surface materials are concentrated in a highly dynamic manner and thus, VHR remote sensing images entail a wealth of details. In the context of such highly dynamic urban environments, object-based approaches for change detection are considered more suitable (Hussain et al., 2013; Lu et al., 2014). Especially in case of multimodal data sources, e.g., VHR imagery acquired by different sensors with deviating viewing geometries, position of the sun, among many others, exact geometric, spectral and radiometric matching of the multi-temporal

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images is almost impossible and object-based methods appear more appropriate and effective (Tewkesbury et al., 2015).

For object-based change detection of multi-temporal VHR data, basically three different methodological approaches are reported in literature (Chen et al., 2012; Hussain et al., 2013; Lu et al., 2014): (1) direct comparison of individual segmentation objects, (2) comparison of classified objects, and (3) simultaneous segmentation and classification of multi-temporal objects. Methods from the *first category* usually perform segmentation of multi-temporal imagery separately and subsequently compare the resulting image objects (Chen et al., 2012). This comparison can be based on either geometrical properties, spectral information, and/or other attributes of the individual image objects (Hussain et al., 2013). The major drawback of methods from this category is that inconsistent geometries of the resulting objects must be detected and handled (Blaschke, 2005). Approaches from the *second group* classify image objects in the individual multi-temporal images in order to derive thematic "from-to" changes (Chen et al., 2012). This technique refers to post-classification comparison in pixel-based change detection (Lu et al., 2004; Singh, 1989) and is probably the most commonly used methodology for object-based change detection (Hussain et al., 2013). Results of these methods are intuitive and straightforward due to the thematic information content (i.e. "from-to" changes) but the methodology and accuracy of the initial classifications are crucial due to error propagation (Chen et al., 2012). Furthermore, geometric inconsistencies can deteriorate the result in case of deviating object geometries (Blaschke, 2005). As a solution to the limitations of the above-mentioned approaches, techniques from the *third category* delineate multi-temporal objects from all scenes simultaneously and generate common image objects for all acquisitions (Hussain et al., 2013). Alternatively, mutual image objects from an external data source (e.g., from Volunteered Geographic Information or existing vector maps) can be utilized. Especially for object-based change detection approaches employing multimodal data sources as presented in this study, the concept of multi-temporal objects is highly beneficial due to consistency in size, shape and location coordinate of image objects over time (Chen et al., 2012; Hussain et al., 2013). Furthermore, Tewkesbury et al. (2015) conclude that multi-temporal objects are likely the most robust analysis unit for object-based change detection.

The technique of multi-temporal objects has been applied successfully for change detection of VHR remote sensing imagery delineating changes of land cover in urban environments (e.g., Im et al., 2008; Doxani et al., 2012; Yang et al., 2015). A special application of change detection in urban areas is damage detection of buildings (i.e. changes that have occurred due to natural hazards such as earthquakes or tsunamis), which is conducted by Al-Khudhairy et al. (2005) using pan-sharpened IKONOS data, while Chen and Hutchinson (2007) deploy correlation analysis on panchromatic QuickBird imagery. Another specific application of change detection with respect to buildings is map updating where (usually) mono-temporal VHR data are utilized for change detection based on outdated (vector) map data. For example, Bouziani et al. (2010) present a supervised change detection approach where existing building geometries are used for learning and classification of IKONOS and QuickBird images, whereas Matikainen et al. (2010) employ VHR aerial imagery and map data for building detection and rule-based change detection. Furthermore, several studies utilizing multi-temporal remote sensing images rely on unsupervised methods for change detection of buildings (Huang et al., 2014; Klonus et al., 2012; Tang et al., 2013). All above-mentioned studies utilize VHR remote sensing imagery from a single sensor with similar viewing geometries. A recent study that presents a change detection approach for imagery from different sensors is Wang et al. (2015), where data from QuickBird and WorldView are simultaneously cross-sharpened in order to detect changes robustly using an unsupervised workflow. However, this particular study presents change detection without focus on individual buildings.

In contrast to the above-mentioned studies, this paper uniquely combines the concept of multi-temporal objects with an adequate representation of object-based features and proposes a novel unsupervised object-based change detection approach using VHR imagery in a dynamic urban environment at the building-level. Furthermore, a very heterogeneous data base is considered, incorporating remote sensing imagery from different sensors with significantly deviating acquisition parameters. In this study, monitoring of urban growth is demonstrated by the example of the Chinese city of Dongying as experimental site. The objectives of this work are as follows: i) development of an unsupervised object-based change detection approach using multi-modal VHR imagery for monitoring of urban growth, ii) quantification of the influence of deviating viewing geometries of optical VHR satellite systems on different platforms and iii) evaluation of several object-based feature sets of different characteristics in order to indicate the basic suitability of distinct types of features for identification of changed buildings.

2. Materials

2.1. Study area

The change detection approach is applied to the Chinese city of Dongying, located in the Yellow River Delta (YRD). The YRD harbors the Shengli Oil Field, which is the second-largest oil deposit in China (Kuenzer et al., 2014). After construction of the first oil wells in the 1960s, the city of Dongying was established in 1983 in order to meet the needs for industrial and residential areas of the oil industry. The YRD together with the city of Dongying is one of China's key regions in terms of economic development (Wohlfart et al., 2016) and thus, the city itself as well as the whole YRD have undergone a rapid economic development during the past four decades (Kuenzer et al., 2014). This is accompanied by highly dynamic urbanization and industrialization, which is well visible in the main city of the YRD, Dongying, where the population already exceeded 800.000 inhabitants within its relatively short history of only 30 years (Editorial Committee of Dongying Statistical Yearbook, 2013). According to Ottinger et al. (2013), the YRD is one of the fastest growing deltas worldwide, which does not only affect urban development of the city of Dongying, but also possibly threatens surrounding natural resources.

The experimental site is a relatively flat area without considerable topography and comprises about 550 buildings for experimental evaluation of the object-based change detection analysis. The distribution of classes (i.e. changed against unchanged buildings) is quite balanced, which is characteristic for the complete city of Dongying as well as for other dynamic Chinese cities with respect to the 6-year period covered by the VHR optical imagery (Fig. 1). Various types of building changes are present within the experimental site, e.g., from bare soil to buildings, from water bodies to buildings, building conversion, etc., whereas the majority of changes correspond to newly built buildings (ca. 80% change from bare soil, ca. 15% change from water bodies) and only a minority (ca. 5%) of changed buildings accounts for building conversion (building conversion is only present in terms of building reconstruction, i.e. demolition and new construction, within the experimental site). For this reason, changed buildings are defined as newly built buildings in this study. Furthermore, different kinds of building occupancies are included, such as industrial usage, shopping malls or residential buildings of different sizes and shapes. The buildings within the experimental site exhibit a variation in building footprint area of 80–18800 m^2 and a height range of few meters