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Evaluation of data fusion and image segmentation in earth observation based rapid mapping workflows

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ABSTRACT

This paper is an exploratory study, which aimed to discover the synergies of data fusion and image segmentation in the context of EO-based rapid mapping workflows. Our approach pillared on the geographic object-based image analysis (GEOBIA) focusing on multiscale, internally-displaced persons' (IDP) camp information extraction from very high spatial resolution (VHSR) images. We applied twelve pansharpening algorithms to two subsets of a GeoEye-1 image scene that was taken over a former war-induced ephemeral settlement in Sri Lanka. A multidimensional assessment was employed to benchmark pansharpening algorithms with respect to their spectral and spatial fidelity. The multiresolution segmentation (MRS) algorithm of the eCognition Developer software served as the key algorithm in the segmentation process. The first study site was used for comparing segmentation results produced from the twelve fused products at a series of scale, shape, and compactness settings of the MRS algorithm. The segmentation quality and optimum parameter settings of the MRS algorithm were estimated by using empirical discrepancy measures. Non-parametric statistical tests were used to compare the quality of image object candidates, which were derived from the twelve pansharpened products. A wall-to-wall classification was performed based on a support vector machine (SVM) classifier to classify image objects candidates of the fused images. The second site simulated a more realistic crisis information extraction scenario where the domain expertise is crucial in segmentation and classification. We compared segmentation and classification results of the original images (non-fused) and twelve fused images to understand the efficacy of data fusion. We have shown that the GEOBIA has the ability to create meaningful image objects during the segmentation process by compensating the fused image's spectral distortions with the high-frequency information content that has been injected during fusion. Our findings further questioned the necessity of the data fusion step in rapid mapping context. Bypassing time-intensive data fusion helps to actuate EO-based rapid mapping workflows. We, however, emphasize the fact that data fusion is not limited to VHSR image data but expands over many different combinations of multi-date, multi-sensor EO-data. Thus, further research is needed to understand the synergies of data fusion and image segmentation with respect to multi-date, multi-sensor fusion scenarios and extrapolate our findings to other remote sensing application domains beyond EO-based crisis information retrieval.

1. Introduction

In humanitarian emergencies, the earth observation (EO) data need to be streamed through time-critical workflows for delivering reliable and effective information (Tiede et al., 2011; Witharana et al., 2013). Thus, there is always a compromise among response time, analysis depth, and thematic accuracy (Voigt et al., 2011). Typically, in the context of an EO-based rapid mapping workflow, the pre-preprocessing step serves as an integral segment that stands in between data acquisition and analysis steps (Witharana et al., 2013). Therefore, the main thrust of our work is to emphasize major steps (e.g., data fusion) involved in the pre-processing segment and explore the effect of those in the proceeding key steps (e.g., image segmentation, classification) of EO-based rapid mapping workflows.

Very high spatial resolution (VHSR) satellite sensors typically record image data in a low resolution multispectral (MS) mode and high resolution panchromatic (PAN) mode (Nikolakopoulos, 2008; Kim et al., 2011). Pansharpening is a pixel-level fusion technique used to increase the spatial resolution of the multispectral image

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while preserving the spectral information (Gangkofner et al., 2008; Makarau et al., 2012). Many data fusion algorithms (commonly categorized as, spectral-domain, arithmetic merging, and spatial-domain methods (Gangkofner et al., 2008; Ehlers et al., 2010; Kim et al., 2011; Yang et al., 2012) have been developed and tested for different application domains. Fusion algorithms introduce spectral and spatial distortions to the resultant data depending on the scene content and the algorithms themselves (Ashraf et al., 2012; Civco and Witharana, 2012; Witharana et al., 2013).

Image segmentation, a process of partitioning of a complex image-scene into non-overlapping homogeneous regions (segments) in scene space, is the primary step within geographic object-based image analysis (GEOBIA) framework (Costa et al., 2008; Dey et al., 2010; Liu et al., 2012; Tong et al., 2012). This step is decisive because the resulting segments (image object candidates (Blaschke, 2010)) form the basis for the subsequent classification, which is based on spectral, structural, topological, and semantic features (Burnett and Blaschke, 2003; Hay et al., 2003; Benz et al., 2004; Lang et al., 2008; Neubert et al., 2008; Marçal and Rodrigues, 2009; Sturm and Weindner, 2009; Smith and Morton, 2010; Tong et al., 2012). When thinking beyond perfect and optimal image object candidates, either of two artifacts are expected in segmentation, i.e. over-segmentation and under-segmentation (Neubert et al., 2006, 2008; Marpu et al., 2010). While the former is acceptable, the latter is highly undesirable and has to be avoided (Sturm and Weidner, 2009).

Humanitarian crisis management remote sensing applications require high spatial and spectral resolution images. In fact, data fusion serves as a cohesive component and routine procedure in EO-based rapid mapping workflows (Witharana and Civco, 2012; Witharana et al., 2013). Similar to other RS applications, the GEOBIA framework is well-established in the crisis management domain (Giada et al., 2003; Al-Khudairy et al., 2005; Tiede et al., 2010, 2011; Lang et al., 2010a,b; Hagenlocher et al., 2012) due to the evident shortfalls of the pixel-based spectral-data alone model when confronted with VHSR imagery. The general view of the data fusion community is that any error in the synthesis of the spectral signatures at the highest spatial resolution causes an error in the decision (Ranchin et al., 2003). This interpretation holds true for pixel-based approaches, however, it can be challenged in the object-based paradigm because of GEOBIA's inherent nature of aggregating pixels into nested and scaled representations (Burnett and Blaschke, 2003), in which image object candidates serve as main building blocks of class labeling rather than single pixels. The GEOBIA framework has the ability to create meaningful image object candidates during the segmentation process by compensating the fused image's spectral distortions with the high-frequency information content that has been injected during fusion. Data fusion and image segmentation are independently addressed in many studies, however the dependency of those two processes has not yet been addressed. We envision increased value of investigating synergies of data fusion and image segmentation in the context of EO-based rapid mapping workflows. Depending on the design goals of fusion algorithms, the pansharpening (e.g., global-scale pansharpening (Kim et al., 2011) process (also the selection of the best fusion method) consumes significant time in rapid mapping workflows. For example, spatial-domain methods (e.g. Ehlers fusion algorithm) are more time- and processor-intensive than arithmetic domain method (e.g., Brovey transform fusion algorithm). The intriguing question is "do time-intensive fusion algorithms, which are typically designed to provide high spatial and spectral fidelity of fused products, make a significant difference in the segmentation process compared to other time-efficient fusion methods?". There is another growing tendency of introducing raw image layers (i.e., PAN image layer and MS image layers) individually to segmentation algorithms (e.g., eCognition Developer's multiresolution segmentation algorithm) and refine resulting image objects during class modeling (Lang et al., 2010a,b). For example, Tiede et al. (2011) attempted to bypass major pre-processing steps, including data fusion, and developed a methodology for automated extraction of damage information from very high spatial resolution (VHSR) satellite image data. In this respect, in light of the GEOBIA framework, the requisite of pansharpening in rapid mapping workflows needs to be explored.

The overarching goal of our continuous research work is to explore novel ways to catalyze EO-based humanitarian crisis information retrieval chain. This paper is centralized on a core objective that aims to investigate the synergies of data fusion and image segmentation in a rapid mapping context. Our study is inspired by the findings of Witharana et al. (2013), in which we employed a detailed multidimensional assessment to understand the performances of twelve application-oriented data fusion algorithms when applied to ongoing- and post-crisis VHSR image scenes comprising earthquake damaged areas of Haiti, flood impacted areas of Pakistan, and armed-conflicted areas and IDP camps of Sri Lanka. Because the current study serves as an exploratory research effort that aims to maintain a greater depth of analysis, we confine our study area to an IDP camp in Sri Lanka.

The rest of the paper is structured as follows. Section 2 describes study area, image data, data fusion algorithms and evaluation methods, image segmentation and quality assessment workflow. Section 3 reports the spatial and spectral fidelity of fused products, quality of image object candidates and statistical significance, and classification and accuracy assessment. Section 4 contains a discussion explaining the results based on the performances of fusion algorithms and the quality of their image object candidates. Finally, conclusions are drawn in Section 5.

2. Materials and methods

2.1. Study area, image data, and analysis workflow

Our study area is of a former war-induced ephemeral settlement, the Menik Farm IDP camp, in Sri Lanka (Fig. 1). According to the joint humanitarian and early recovery reports of the United Nations Coordination of Humanitarian Affairs (UNOCHA), in late February 2010, the Menik Farm IDP camp hosted approximately 93,000 individuals (~28,000 IDP families). Owing to the Sri Lankan government's well-defined post-war resettlement, recovery, and livelihood restoration strategies, this IDP camp was decommissioned within a short time-window. The selection of study areas was made mainly focusing on the value of ongoing-crisis humanitarian information extraction. The image scene used in this study was acquired by GeoEye-1 sensor in February 2010. The GeoEye-1 sensor has a spatial resolution of 0.41 m for the PAN and 1.65 m for MS bands at nadir with 11-bit radiometric resolution. We extracted two subset sites (MF1 and MF2, each approximately 1 km × 1 km) from the whole scene (Fig. 1) and introduced them to image fusion and segmentation workflows (Fig. 2).

2.2. Methods

2.2.1. Image fusion and quality evaluation

Our candidate data fusion algorithms entailed: (1) Brovey transform fusion (BT), (2) Color normalization (CN) spectral sharpening, (3) Ehlers fusion (EH), (4) Gram-Schmidt (GS) fusion, (5) High-pass filter (HPF), (6) Local mean matching (LMM), (7) Local mean variance matching (LMVM), (8) Modified intensity hue saturation (MIHS), (9) Principal component analysis (PCA), (10) Substrative resolution merge (SRM), (11) university of New Brunswick (UNB) fusion, and (12) Wavelet Transform-PCA (WV-PCA). Fusion results were introduced to a series of quality metrics along with detailed