Automation of Change Detection Procedures for Nuclear Safeguards-Related Monitoring Purposes

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***Abstract* - Against the background of nuclear safeguards applications using commercially available satellite imagery, a two-steps attempt for change detection and analysis was realized in general. Beginning with the wide-area monitoring on the basis of medium-resolution satellite data for the pre-scanning of significant changes within the nuclear-related locations, the areas of interest could then be explicitly analyzed by change detection and analysis methods using high-resolution satellite data. The change pixels were detected by using the multivariate alteration detection (MAD) transformation, producing a set of mutually orthogonal difference images (the so-called MAD variates). The decision thresholds for the change pixels were set by applying a probability mixture model to the MAD variates based on an EM algorithm. By means of *eCognition* a second, object-oriented procedure was implemented in order to create an automated workflow for the multiscale extraction of the (change) objects and (change) features for the subsequent post-classification of the areas of interest. Regarding the necessity of automation for extensive monitoring tasks the processing aspects of standardization and transferability took the centre stage of the investigations.**

Keywords: change detection, pixel-based techniques, object-oriented techniques, automation, nuclear safeguards,

I. Introduction

Since high-resolution satellite imagery is commercially available, the use of remote sensing data has become very important for nuclear safeguards purposes. Today, the high spatial resolution satellite imagery provides a good basis for recognizing and monitoring even small-scale structural changes within nuclear facilities and for planning of routine and/or challenge inspections of nuclear sites, see [1] for a comprehensive overview. Assuming a finer temporal resolution satellite imagery could be more and more build the basis for complex nuclear monitoring systems. When using a huge amount of image data, the analysis within the system including pre-processing steps, detection of change pixels and classification of changes should be carried out as automatically as possible.

II. Change Detection

A comprehensive wide-area change detection system for nuclear verification purposes has to imply preferably automated procedures for geometric registration, radiometric normalization, image fusion/sharpening and statistical change/no-change detection and analysis of medium- or high-resolution imagery. In the given paper the main emphasis was put on the detection and analysis of change pixels.

For the detection of change pixels, several statistical techniques exist, calculating the spectral or texture pixel values, estimating the change of transformed pixel values or identifying the change of class memberships of the pixels. Depending on the requirements of the image data as to spatial, spectral and temporal resolution, these algorithms differ thus with respect to the measure of change used. But when adopted to high-resolution imagery, the results of these pixel-based algorithms are sometimes limited. Especially if small structural changes are to be detected, object-oriented procedures seem to be more precise and meaningful.

A. Pixel-based change detection

When a change signal within nuclear sites is very significant in terms of grey value change or expanse, it can mostly be detected by the pixel-based analysis of mid-resolution multispectral image data.

For the specific application of nuclear monitoring the most satisfactory results were carried out by the so-called Multivariate Alteration Detection (MAD) transformation [2]. The MAD procedure is based on a classical statistical transformation referred to as canonical correlation analysis to enhance the change information in the difference images and briefly described as follows: If multispectral images of a scene acquired at times t_1 and t_2 are represented by random vectors X and Y, which are assumed to be multivariate normally distributed, the difference D between the images is calculated by

$$D = a^T X - b^T Y .$$

Analogously to the principal component transformation, the vectors a and b are sought subject to the condition that the variance of D is maximized and subject to the constraints that $\mathrm{var}(a^T X) = \mathrm{var}(b^T Y) = 1.$. As a consequence, the difference image D contains the maximum spread in its pixel intensities and - provided that this spread is due to real changes between t_1 and t_2 - therefore maximum change information. Determining the vectors a and b that way is a standard statistical procedure which amounts the so-called generalised eigenvalue problem. For a given number of bands N, the procedure returns N eigenvalues, N pairs of eigenvectors and N orthogonal (uncorrelated) difference images, referred to as to the MAD variates. Since relevant changes of man-made structures will generally be uncorrelated with seasonal vegetation changes or statistic image noise, they expectedly concentrate in the higher order components (if sorted according to the increasing variance). Furthermore, the calculations involved are invariant under affine transformation of the original image data. Assuming that changes in the overall atmospheric conditions or in sensor calibrations are approximately equivalent to affine transformations of the pixel intensities, the method is insensitive to both of these effects

The decision thresholds for the change pixels could be set in terms of standard deviations about the mean for each MAD component. Regarding automation a probability mixture model was applied to the MAD variates based on a simple EM algorithm to determine automatically the density functions for the change and no-change pixels and thence the optimal decision thresholds for discriminating change and no-change pixels. The mixture-model procedure was proposed by [3] and already applied for instance in [4].

B. Object-oriented change detection and analysis

Significant changes can then explicitly be analyzed and interpreted by object-oriented approaches using high-resolution satellite imagery. Analyzing satellite image data in an object-oriented way generally gives the possibility to involve specific knowledge in the classification or recognition process. Preliminary results have already indicated that the analysis and interpretation of changes within nuclear plants can be more precisely and reliably if the change detection procedure makes use of the characteristic features of facility objects and changes (e.g. compared to other industrial sites) [5]. The software solution for an object-oriented change analysis is currently given by *eCognition* [6].

Against the background of nuclear safeguards applications, a combination of pixel-based techniques for the detection of changes pixels and object-oriented procedures for the subsequent analysis respectively classification of the change pixels was investigated. Regarding the automation of the processing aspects of standardisation and transferability took the centre stage of the investigations.

III. INVESTIGATIONS

An image database for 17 nuclear-related locations of the Iran was set up within *eCognition Enterprise* as basis for the intended investigations, including multitemporal area-wide ASTER imagery (AST_07, surface reflectance with 15m (VNIR) and 30m (SWIR) spatial resolution) and supplement by high-resolution imagery from QUICKBIRD for a few areas of interests; see [7] for more information.

A. Pre-scanning: Wide-area monitoring using medium-resolution satellite imagery

The so-called pre-scanning is intended for the detection of potential nuclear-related undeclared activities and the detection of major changes within declared nuclear sites and their surrounding areas. ASTER imagery of the Iranian nuclear sites located at Arak, Bandar Abbas, Busheer, Esfahan and Natanz were used as training data in order to determine a fixed set of segmentation parameters for a sufficient multiresolution object extraction, to define satisfactory and transferable object features for object classes that are relevant in terms of nuclear safeguards and to implement a measure for possibly changes within nuclear facilities.

For the standardization of the object extraction both solely multiresolution segmentation and a combination of chessboard and multiresolution segmentation was carried out, as described in [7] (Fig. 1). The subsequent automated feature extraction with respect to a standardized and transferable semantic classification model was supported by a statistical procedure analyzing the separability between two classes, see again [7] for more information. In the next step it was tempted to implement a measure for potential changes within industrial facilities. On the basis of the co-registered bitemporal data sets change pixels were detected by using the MAD transformation (Fig. 2).

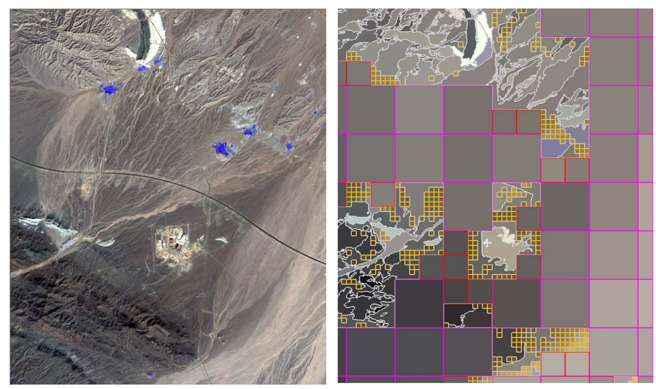

Figure 1. Extract of AST07, green (R), red (G), NIR (B) over Natanz (left) and its chessboard/multiresolution segmentation, level 6 (right)

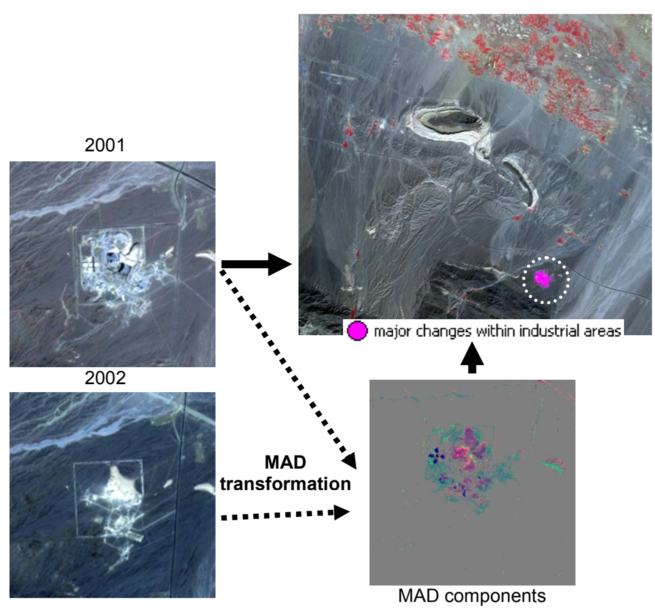

Figure 2. Classification of industrial areas with enclosed significant changes, Natanz 2001-2002

As shown in Fig. 2, these so-called MAD variates symbolize no change at all grey-colored pixels (of course dependent on the normalization of the MADs), while the pixels different from grey indicate changes. Imported as additional information layers they provided a measure of change within the semantic model.

B. Detailed change detection and analysis using high-resolution imagery

If areas with significant, safeguards-related changes have been detected on the basis of the medium-resolution image data, they then will be analyzed in detail using high-resolution imagery. Finally, the possibilities to automate change detection and analysis procedures using high-resolution image data were examined, given an extract of the 2002 and 2003 QUICKBIRD images over the Esfahan NFRPC.

A bi-temporal extract from the QUICKBIRD imagery was analyzed. Since both image data sets were acquired nearly at the same time of the year, 24 of July 2002 respectively 9July 2003 at about the same daytime, seasonal variations were estimated to be minimal. Unfortunately the images were taken with different sensor positions (24.07.2003: Off Nadir Angle 9°, Target Azimuth: 226°/ 09.07.2003: Off Nadir Angle 15°, Target Azimuth: 283°), thus the parallaxes differ slightly. In order to solve this problem, the orthorectification of the imagery seemed to be reasonable. Until now, no orthorectification was consequently applied to the two data sets3. After all, the pre-processing was done by manual image-to-image-registration and by using the ENVI implementations for Wavelet-based image sharpening. The algorithms will not be discussed here, please see [8,9] for more information.

For the two pre-processed image extracts the following changes can be expected: Changes due to the different sensor positions (different parallax), real changes in terms of nuclear safeguards and other significant changes land cover or land use. For this purpose a combination of pixel-based techniques for the detection of changes pixels and object-oriented procedures for the subsequent analysis respectively classification of the change pixels was proposed.

The change pixels were again detected by using MAD transformation, and the decision thresholds for the change pixels were set by applying the probability mixture model to the MAD variates. Fig. 3 shows the resulting MAD variates with automatic and increased thresholds, coloured pixels indicate changes while grey pixels represent no changes.

Assuming that an object-oriented approach could improve the results, we implemented a second procedure. As input data for the object extraction within *eCognition*'s multiscale segmentation the four MAD change components Different segmentation parameters were applied to both data sets in different scales, so that the individual objects of the nuclear plant are extracted in a fine level. By increasing the scale parameter the objects become coarser, until the areas of interest in terms of changes were included in one object (Fig. 4).

The feature extraction within *eCognition* was organized on the basis of the four MAD components. The correlation between input bands and MAD variates was used to derive indications, whether a general increase or decrease of grey values occurred. Moreover, a vegetation index (SAVI) was set up in order to differentiate vegetation areas from non-vegetation areas (and probably man-made structures) respectively transitions between both states. By combining both features, two classes for changes of man-made structures were defined. Fig. 5 shows thus the most significant changes between July 2002 and 2003: The completion of buildings and the partly asphalting of the unmetalled roads.

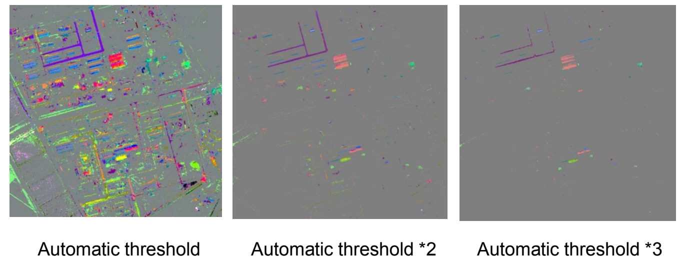

Figure 3. MAD components 1 (red), 2 (green) und 3 (blue) with (increased) automatically estimated threshold

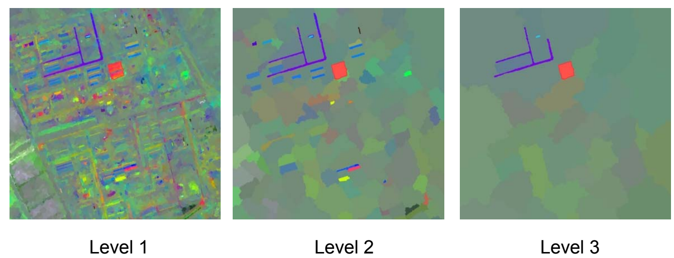

Figure 4. Segmentation levels for the MAD variates

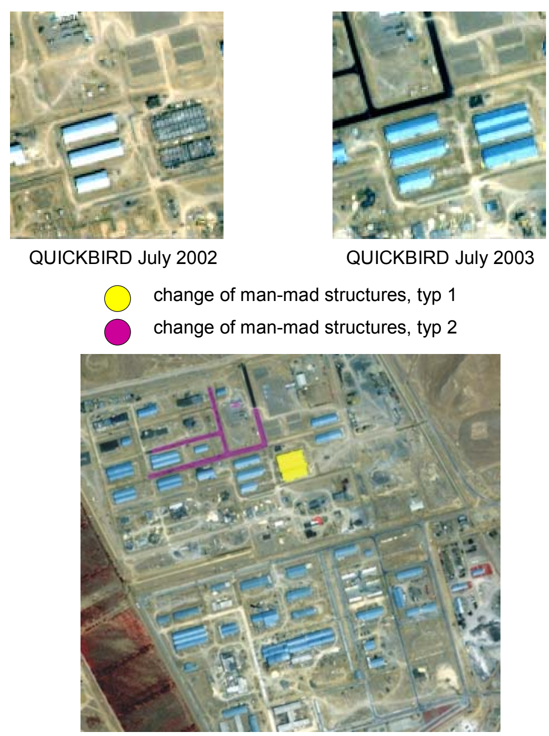

Figure 5. Change analysis 2002-2003 for parts of the Esfahan Nuclear Fuel Research Centre (NFRPC) with respect to two types of mad-made structure changes

IV. CONCLUSIONS

A two-steps attempt for change detection and analysis for nuclear safeguards applications using commercially available satellite imagery was proposed. By means of pixel-based change detection and object-oriented post-classification by *eCognition* some investigations were carried out in terms of automation, thus standardization and transferability. As a result, medium-resolution imagery could be considered as suitably for change-/no change-analysis in terms of wide area monitoring, for the detailed object-oriented analysis of significant changes high-resolution satellite imagery should be used.

The automation and the transferability of the change detection and analysis procedures appears to be feasible to a certain extent, therewith giving rough and fast indications of areas of interest and explicitly analyzing the relevant areas.

Recent problems are connected to the question, how to compare segmentation levels with different object boundaries in (the usual) case of different off-nadir angels. Parameters have to be found in order to quantify and qualify an object's change between two acquisitions times. An optimal set of input image (original, normalized, artificial) and GIS (topographic maps, site diagrams etc.) layer has to be defined. Relevant classes have to be defined by objects features and class relations and the change matrix has to be specified.

For a comprehensive change detection and interpretation system signatures for different facility types in different geographical/ political areas are urgently needed. Thus, the features of the different elements of the nuclear fuel cycle - mining/milling, uranium enrichment, fuel fabrication, reactor (civil power plant), reprocessing plant, waste storage facility have to be further analysed and utilised for image processing.

Moreover, also the automation of the procedures for geometric registration, radiometric normalization, image fusion/sharpening has to be improved or even brought forward.

ACKNOWLEDGMENT

This paper is an outcome from the Global Monitoring for Security and Stability (GMOSS) Network of Excellence in the aeronautics and space priority of the Sixth Framework Programme, please see http://intelligence.jrc.cec.eu.int/gmoss/gmoss.html for more information.

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