Automation of change detection procedures for nuclear safeguards-related monitoring purposes

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Abstract – According to the expected technical improvements regarding the spatial and spectral resolution, satellite imagery could be more and more build the basis of complex systems in the future for recognizing and monitoring even small-scale and short-term structural features of interests within nuclear facilities, for instance construction of buildings, plant expansion, changes of the operational status, underground activities etc.
A "nuclear monitoring system" for the Iran based on *eCognition* was set up to implement and evaluate different image analysis approaches that could be relevant for nuclear safeguards applications. Regarding the necessity of automation for extensive monitoring tasks the processing aspects of standardization and transferability took the centre stage of the investigations.

Keywords: non-proliferation treaty, nuclear safeguards, change detection, pixel-based techniques, object-oriented techniques, automation.

1. NUCLEAR SAFEGUARDS & SATELLITES

The importance of satellite imagery for monitoring and verification of multilateral agreements has been effectually demonstrated for the Non-Proliferation Treaty (NPT). The treaty aims to prevent the spread of nuclear weapons and weapons technology and to support the peaceful uses of nuclear energy under international safeguards. Moreover the treaty commits the member states to achieve (nuclear) disarmament. Entered into force in 1970, a total of 188 countries have now joined the treaty, including five nuclear-weapon states. With this number more countries have ratified the NPT than any other arms limitation and disarmament agreement. The NPT establishes a safeguards system under the responsibility of the International Atomic Energy Agency (IAEA). Safeguards are used to verify compliance with the NPT through inspections conducted by the IAEA.
The discovery the clandestine nuclear weapons development in the NPT member state Iraq in the early 1990s highlighted the weaknesses of the safeguards systems focusing only on declared nuclear material and activities. Therefore the IAEA Board of Governors adopted a model protocol in 1997, expanding the IAEA's inspection authority in the (so far 65) non-nuclear weapon states having ratified this "Additional Protocol" (INFCIRC/540). Under the so-called integrated safeguards combining the primary safeguards based on the Model Agreement (INFCIRC/153) for non-nuclear weapon states and the safeguards based on the Additional Protocol, IAEA has been provided with improved access possibilities to all aspects of a non-nuclear weapon state's nuclear program, even where nuclear material is not involved. In order to strengthen the nuclear safeguards, new verification technologies are needed to gain more detailed information on the member state's nuclear program. As a non-intrusive monitoring method the use of commercial earth observation satellites from earth has taken into account. The potential of satellite image data ranging from panchromatic, multispectral, hyperspectral to radar for site description and change detection has been presented in many case studies, for a comprehensive overview please see (Jasani & Stein, 2002).

According to the expected technical improvements regarding the spatial and spectral resolution, satellite imagery could be more and more build the basis of complex systems in the future for recognizing and monitoring even small-scale and short-term structural features of interests within nuclear facilities, for instance construction of buildings, plant expansion, changes of the operational status, underground activities etc. Large volumes of multispectral satellite data from different sensors require a high degree of automated image (pre-) processing, analysis and interpretation in order to extract the features of interest.
Though it seems to be too overconfident to replace an image analyst completely by a software system, there might me some possibilities to obtain faster and more precisely image analysis results. In order to detect changes within the observation period or reach other analysis tasks on the imagery stored in the database, the areas of interests are traditionally retrieved by a query on the metadata and analyzed subsequently. A more advanced approach would be to realize the analysis already in the retrieval process as an image content-based query. Thus, it could be possible to realize queries like "find areas with huge construction projects", "find areas with significant changes of industrial sites between 2002 and 2004", "find all areas with industrial sites located nearby water", and others on the database image data .

2. 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. 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.

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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) (Niemeyer & Canty, 2003). The software solution for an object-oriented change analysis is currently given by eCognition Professional resp. Enterprise[1](Baatz et al., 2004).

3. NUCLEAR MONITORING IRAN

Seeing the recent proliferation implications of Iran`s advanced nuclear program due to the potential of dual-use activities within uranium enrichment and reprocessing (IAEA, 2004), a so-called nuclear monitoring system for the Iran was set up as an application (Figure 1). In the first instance, multitemporal area-wide ASTER imagery (AST_07, surface reflectance with 15m (VNIR) and 30m (SWIR) spatial resolution) for 17 nuclear-related locations built the database for this system, accompanied by different kind of open source information and completed by high-resolution imagery from QUICKBIRD for some areas of interests. More satellite image data could be added later on demand.

Figure 1. Nuclear monitoring system for 17 nuclear-related locations in the Iran

Different image analysis approaches probably relevant for nuclear safeguards applications were implemented and evaluated. In general, a two-steps attempt was realized beginning with the wide-area monitoring on the basis of the medium-resolution ASTER data for the pre-scanning of areas of interest, i.e. significant changes within the nuclear-related locations, which then could be explicitly analyzed by change detection and analysis methods using the high-resolution QUICKBIRD image data. Regarding the necessity of automation for extensive monitoring tasks the processing aspects of standardization and transferability took the centre stage of the investigations.

3. INVESTIGATIONS

3.1 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 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. With respect to an acceptable computing time the latter segmentation was conducted as follows: After segmenting the image into a coarse chessboard grid, homogeneous chessboard cells with mean standard deviations in the VNIR channels below a specific threshold were excluded from the further segmentation, assuming that homogenous cells defined that way are unlikely to contain small-scale anthropogenic structures. The remaining cells were then divided in a finer chessboard, homogenous chessboard cells removed again on the basis of the standard deviation, the residual cells tiled into a yet finer grid and so on until reaching the defined minimum cell size. Only the pixels left thereafter were finally involved in the more time-consuming multiresolution segmentation process (Figure 2).

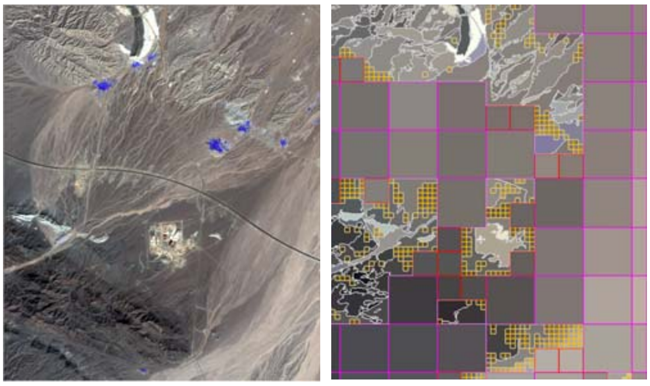

Figure 2. Extract of AST_07, green (R), red (G), NIR (B) over Natanz (left) and its chessboard/multiresolution segmentation, level 6 (right)

For the subsequent object classification a standardized and transferable semantic model being able to perform satisfactory results for all given ASTER (AST_07) scenes was meant to develop. In order to avoid the likewise time-consuming "trial-and-error" practice while seeking for significant class separating object features attempts towards an automatic feature extraction were undertaken. In the given project the optimal object features and the range of its membership functions were automatically determined by a statistical procedure analyzing the separability between two classes. The object classes had been labeled as industrial areas, mountainous areas, settlements, soils, vegetation, water and unclassified before. By this means, a classification model was defined and applied to a number of scenes. Figure 3 shows the classification result for the scene of Bandar Abbas. The relevant site was correctly classified as industrial area, and another one in the left range, too. Water, vegetation and settlements were indicated sufficiently aside from some misclassifications.

[1] http://www.definiens-imaging.com

Anyhow, without adapting the classification model for each scene, the results could be qualified as good to quickly get a general idea of the different land cover classes.

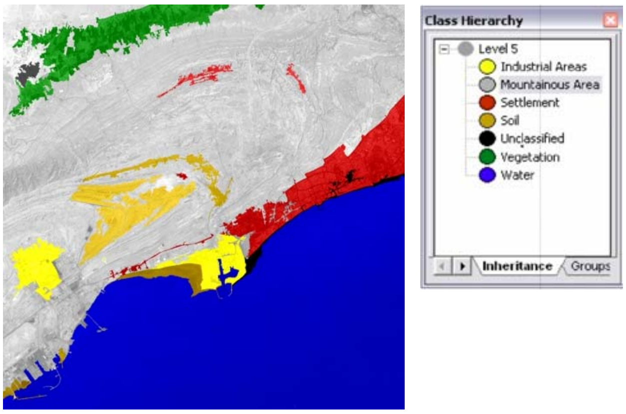

Figure 3. Application of the automated classification model to the ASTER scene of Bandar Abbas

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 multivariate alteration detection (MAD) transformation (Nielsen et al. 1998), producing a set of mutually orthogonal difference images. As shown in Figure 4, 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.

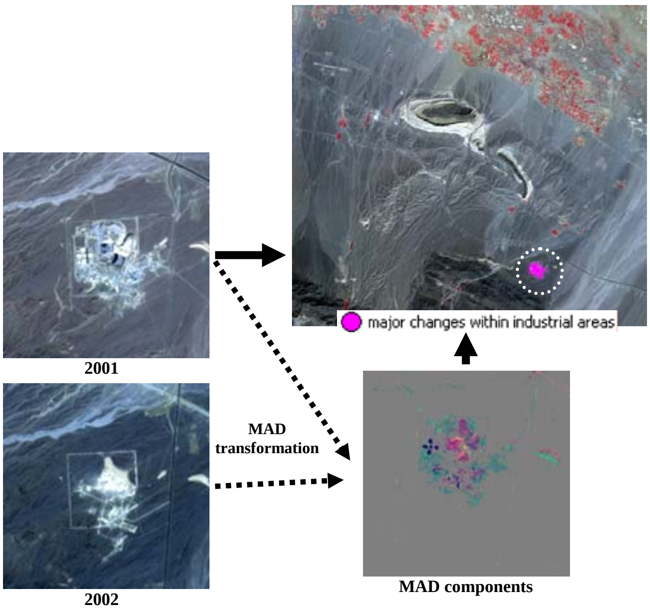

Figure 4. Classification of industrial areas with enclosed significant changes, Natanz 2001-2002

3.2 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. Again, investigations were conducted as to the standardization and transferability of classification models. A QUICKBIRD scene acquired over the Esfahan Nuclear Fuel Research Centre (NFRPC) in July 2002 provided the basis for automatic feature extraction for the classification model. As before, the optimal object features and the range of its membership functions were automatically determined by a statistical procedure analyzing the separability between the classes, in this case between the classe background, built-up areas, roads, shadows and vegetation. When applied to the image data, an overall accuracy of approximate 90% was achieved, depending on the respective segmentation level (Figure 5). In order to check the temporal transferability the 2002 classification model was applied to another image acquired over the Esfahan Nuclear Fuel Research Centre (NFRPC) in July 2003. After minor changes of the 2002 model in reference to one single feature, an overall accuracy of approximate 80% was obtained (Figure 6).

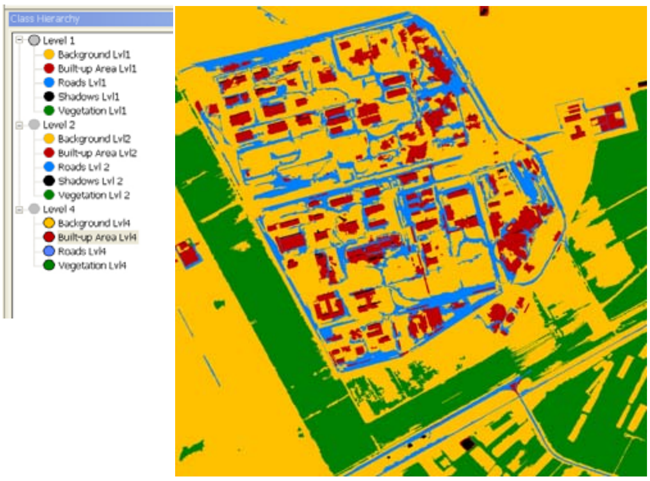

Figure 5. Object-oriented classification of the 2002 QUICKBIRD image over Esfahan Nuclear Fuel Research Centre (NFRPC)

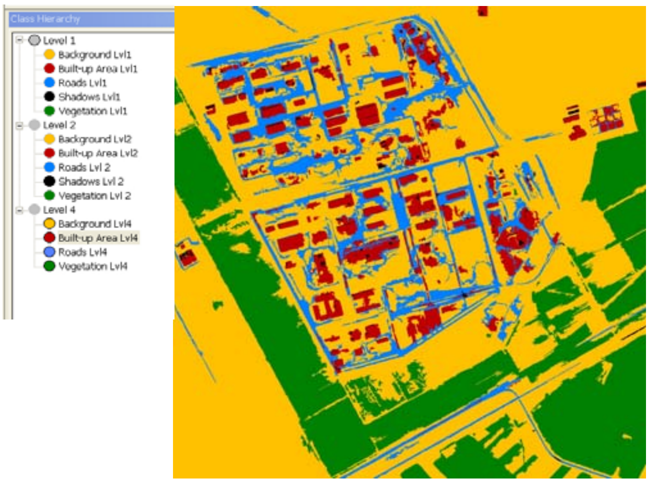

Figure 6 Object-oriented classification of the 2003 QUICKBIRD image over Esfahan Nuclear Fuel Research Centre (NFRPC)

Moreover, the 2002 classification model was tested regarding the spatial transferability by applying it to another extract of the full QUICKBIRD scene (without figure).

Finally, the possibilities to automate change detection and analysis procedures using high-resolution image data were examined. 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. Given an extract of the 2002 and 2003 QUICKBIRD images over the Esfahan NFRPC, an MAD transformation was carried out in order to find the change degree for each pixel. The four MAD components (according to the number of input channels) were used for the object extraction within eCognition. A classification model distinguishing between two types of man-made structure changes was defined by combining the objects mean MAD values, the objects mean spectral values and indices, the correlation between MAD components and original image data, and relations between the objects. Figure 7 shows thus the most significant changes between July 2002 and 2003: The completion of buildings and the partly asphalting of the unmetalled roads.

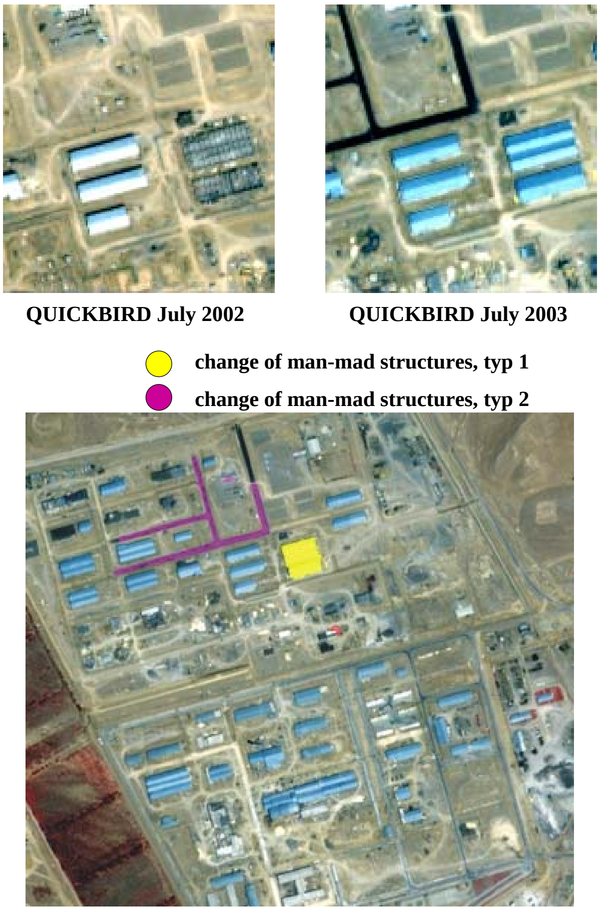

Figure 7. Change analysis 2002-2003 for parts of the Esfahan Nuclear Fuel Research Centre (NFRPC) with respect to two types of mad-made structure changes

3. CONCLUSIONS & OUTLOOK

An object-oriented monitoring system for nuclear safeguards purposes was proposed in order to detect (undeclared) changes within nuclear facilities. 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.

For the advanced analysis of nuclear sites (using high-resolution imagery), a detailed classification model furthermore has to be able to differentiate between nuclear and non-nuclear industrial sites and preferably between the different types of facilities within the nuclear sites class, too. Though the preliminary results within this project and previous approaches on the automated object-oriented classification of German nuclear power plans have been somewhat promising up to now, a lot of case studies have to be performed for a comprehensive understanding of the nuclear sites signatures identifiable in satellite imagery. Furthermore, the attempts to extract the objects features automatically have to be continued and the accuracy of the classification in terms of spatial and temporal transferability needs to be assessed in detail.

6. REFERENCES

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