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Accuracy Assessment of Change Detection Algorithm for Satellite Imagery in Support of Interpretation of Nuclear Activities

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1. Introduction

In the field of nuclear nonproliferation, remote monitoring and on-site inspection are conducted to ensure that nuclear energy is used for peaceful purposes. In this course of implementation, satellite information is being used to establish a site inspection plan, to verify correctness and completeness of nuclear material and facilities. Further, it is used as a means to identify and detect suspicious activity in rogue states that have attempted to proliferate nuclear weapons, not complying with the international nonproliferation regime.

In the past decades, urban expansion, changes in shorelines and prediction of crop yields were analysed with the image quality of a few hundred meters. On the other hand, defence and security have recently begun to utilise the sub-meter level. For countering nuclear proliferation, observations of small-scale activities, such as the movement of vehicles within a nuclear complex, hot water discharge, steam generation and building construction/renovation, enable the estimation of nuclear-related activities [1]. This process demands a sophisticated visual interpretation of as little as a few pixel changes within an area of interest, spanning tens of square kilometres, which involves expertise in the nuclear fuel cycle and weapon development. Against this backdrop, efforts are being made to improve analytical efficiency by developing algorithms that detect small-scale changes [2-4].

In general, the accuracy of change detection algorithm in computer vision is presented in the form of a confusion matrix in units of pixels. For the purpose of identifying nuclear activities, however, the accuracy of the change detection algorithm has not been evaluated for some reason. In this regard, this research investigates the applicability of the traditional method of accuracy assessment for small-scale changes related to nuclear activity in high-resolution satellite imagery and provides a guideline for proper criterion.

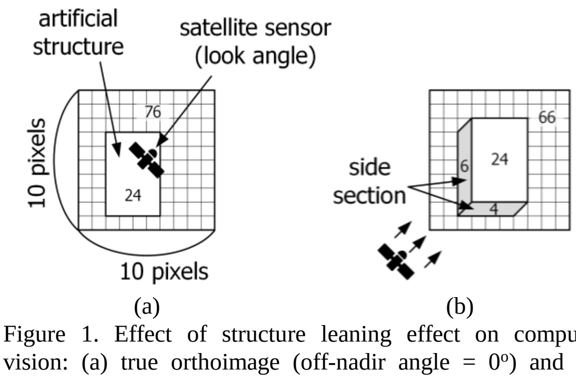
The following Section summarises algorithm-based change detection to counter nuclear proliferation and reviews the underlying cause, which makes a quantitative assessment of the algorithm challenging. The results of applying the traditional method for accuracy assessment and requirements of proper criterion to counter nuclear proliferation are discussed in Sections 3 and 4, respectively. The conclusions are set forth in Section 5.

2. Peculiarities of algorithm-based change detection for countering nuclear proliferation

Until the 1970s, satellite information was exclusively owned by advanced technology holders such as the United States and Russia. Since the mid-1990s, accessibility of commercial satellite information increased, allowing for the distribution of sub-meter satellite images with the amount of acquired information increasing simultaneously. The commercial operation of small satellites in recent decades increased the demand for automation technology which can detect nuclear-related activities in satellite imagery. With this background, the applicability of an algorithm for change detection has been studied [2-4].

In order to recognise any changes between two images by an algorithm, the positions for each pixel of the two images have to be geometrically aligned with each other so that corresponding pixels represent the same objects except for changed ones. When acquiring satellite images, the side section of artificial structures appears on the image due to the effect of the off-nadir angle (oblique image). The multiple aerial (or drone) imaging and height of the structure are required to correct this to a true orthoimage. In the case of nuclear proliferation states, however, access to the states are restricted. Under this circumstance, changes to the structure have to be determined with oblique images.

Figure 1 shows that the pixels due to the off-nadir angle of the satellite (sensor) are on the image. Despite there being no actual change, the position of the structure (roof) is shifted along with the appearance of the side section of the structure (Fig.1b) which is not



(a) (b)

Figure 1. Effect of structure leaning effect on computer vision: (a) true orthoimage (off-nadir angle = 0°) and (b) oblique image (off-nadir angle ≠ 0°)

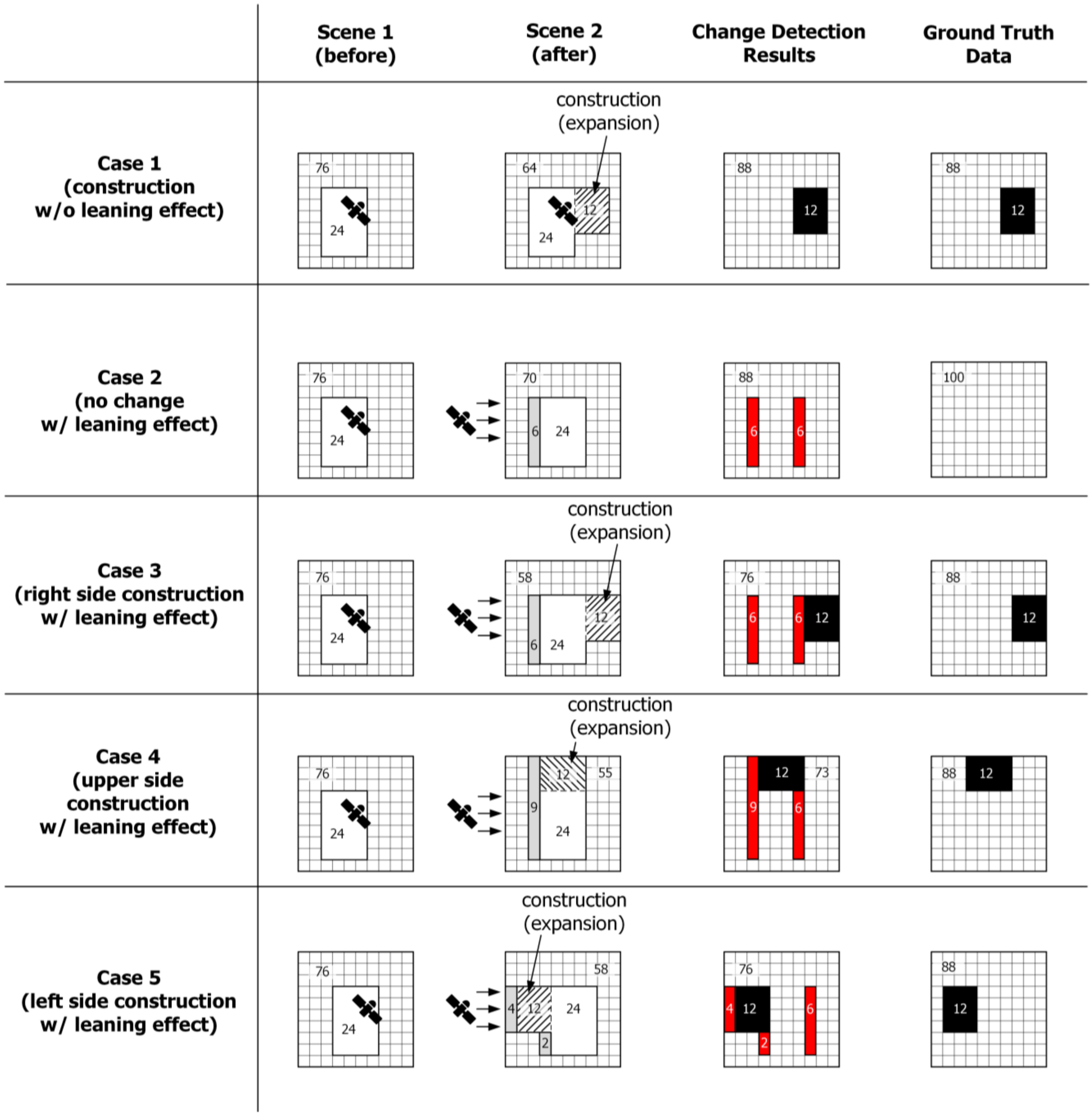


Figure 2. Visualisation of accuracy assessment for case studies showing structure leaning effects

Table 1. Confusion matrix for case studies in Fig. 2.

			True Condition (Ground Truth Data) Positive	True Condition (Ground Truth Data) Negative
Predicted (Algorithm)	Case 1	Positive	12	0
		Negative	0	88
	Case 2	Positive	0	12
		Negative	0	88
	Case 3	Positive	12	12
		Negative	0	76
	Case 4	Positive	12	15
		Negative	0	73
	Case 5	Positive	12	8
		Negative	0	80

Table 2. Evaluation of accuracy, precision, recall, F1-score and false discovery rate for case studies in Fig. 2.

	Overall accuracy	Precision (positive predictive value)	Recall (true positive rate)	F1-Score	FDR (false discovery rate)
Case 1	1.00	1.00	1.00	1.00	0.00
Case 2	0.88	0.00	-	-	1.00
Case 3	0.88	0.50	1.00	0.67	0.50
Case 4	0.85	0.44	1.00	0.62	0.56
Case 5	0.92	0.60	1.00	0.75	0.40

present in the true orthoimage (Fig.1a). This is a residual error after pre-processing of satellite images when applying to algorithm-based change detection. Even if the ground of the two images is correctly registered, it affects the accuracy assessment of algorithm-based change detection. Several studies [3, 5, 6] have been conducted in the past to detect nuclear-related activities. The studies, however, analysed the change detection results qualitatively not quantitatively. From the defence and security perspective, potentially suspicious activities must be detected without missing. This mission without necessary data is not only peculiarities also challenges to performing algorithm-based change detection for countering nuclear proliferation.

3. Traditional methods for accuracy assessment

A method of evaluating performance for an algorithm has to be determined based on the purpose of the application. The change detection in the computer vision and geographical information systems (GIS) means a process that measures how the attributes of the area of interests have changed between two (or more) images [12]. Hence, after producing binary masks (a change/no change in each pixel concerned), a confusion matrix, also known as an error matrix, is calculated. Then, the overall accuracy, precision, recall, F1-score, and false discovery rate (FDR), which are widely used for accuracy assessment of change detection is derived from the confusion matrix. For the sake of limited space, each definition and formula is not described herein. The detailed information can be found in [7].

Figure 2 illustrates case studies to depict the effect of the off-nadir angle on the pixel occupation. The expansion of a building was chosen as it can be interpreted as one of the major signs of increasing capacity for uranium concentration [8]. Case 1 is true orthoimages (ideal case) for with construction change, and Case 2 is for no change between the actual images with an effect of the off-nadir angle. Cases 3 to 5 intend to have the effect of the actual change and the off-nadir angle simultaneously.

It is assumed that the change detection algorithm detects all changes (true positive rate = recall = 100%; false negative = none) to simplify the problem. The total number of pixels is one hundred (10×10), and true and false positives are labelled in black and red, respectively.

By the results of Fig. 2, Tables 1 and 2 summarise the confusion matrix and evaluation of the traditional method for the five case studies. Compared with the accuracy assessment [9, 10] of recent research on change detection algorithms (approximately over 80%), the precision (ranging from 44% to 60%), which is the most relevant index for defence and security applications, seems not feasible from the engineering perspective. Likewise, the false discovery rate indicates 50% on average. It is easily understandable from the red pixels (i.e., residual error) in Fig. 2 by comparing with the number of actual change pixels in black. To overcome the structure leaning effect, there is an algorithm technique that excludes the red pixels from the change for narrow, elongated areas [11]. Nonetheless, when the area occupied by the side of the building increases, the false positive proportionally increases, and all accuracy indices decrease accordingly. At this point, it is worth discussing how the output of the algorithm is supposed to post-process for the purpose of countering nuclear proliferation.

4. Requirements for accuracy assessment in support of interpretation

The key to proper accuracy assessment is directly linked to the aim of developing and applying the algorithm. To counter nuclear proliferation, the output of the algorithm always needs to be interpreted by imagery analysts [3], due to the fact that it requires not only ability in remote sensing and GIS but also expertise in the nuclear fuel cycle and weapon development. The output of the change detection algorithm intends to improve the efficiency of imagery analysts of nuclear activities. Accordingly, the criterion of the algorithm-based change detection in support of nuclear activity interpretation should differ from the applications where secondary analysis is impossible or occasionally unnecessary, such as urban expansion, coastline change, and crop yield prediction.

The construction in Fig. 2 is fully detected based on the assumption, true positive rate = recall = 100%. By changing the assumption, if the algorithm results in six pixels of true positive (labelled in black) which is half of the 12-pixel building expansion, the recall is reduced by 50%. Nonetheless, in terms of supporting the imagery analysts, the algorithm completes its role as intended, offering an opportunity to see the actually changed area. From an image analyst perspective, efforts to recognise the existence of changes do not vary significantly whether the number of pixels representing the area on the side of the building increases or decreases. The matter is the number of individual enclosed objects (a group of pixels) that need to be closely monitored. Therefore, the traditional method for accuracy assessment is not suitable for evaluating the performance of the change detection algorithm in support of nuclear activity interpretation. Instead, the number of detected enclosed areas (objects) provided by the algorithm is a significant indicator to evaluate the accuracy of the algorithm. To sum up, there are two key questions on the output: (1) how many of the detected enclosed areas have actually changed pixel(s) and (2) how many of the detected enclosed areas do not have pixel(s) of actual change.

5. Conclusions

This study sheds light on the peculiarities of algorithm-based change detection to counter nuclear proliferation. Subsequently, the applicability of the traditional method for accuracy assessment was investigated considering the effect of off-nadir angle on high-resolution satellite images. It showed that the method is not feasible from the engineering perspective.

Given the purpose of the algorithm in support of interpretation, a guideline for evaluating the performance of the change detection algorithm has been proposed. It has been concluded that from the image analyst perspective, it is important not to miss the change of objects, instead of focusing on the pixel(s). The key is how to minimize the number of detected enclosed areas (objects) which do not have pixel(s) of actual change.

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