Change Detection on Millimeter-Wave SAR Images for C-IED Applications

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Abstract

Countering improvised explosives devices (IEDs) is a major concern for troops in peacekeeping and peace-enforcing missions: the threat to become a victim of terrorist's attacks by IEDs is present everywhere. Sensors onboard of unmanned areal vehicles (UAVs) are one option to be able to survey a larger terrain for IEDs. Among other imaging sensors, synthetic-aperture radar (SAR) can contribute to detect and classify the signature of suspicious devices on the ground. Experiments have been conducted with a millimeter-wave SAR operating simultaneously at 35 GHz and 94 GHz. Generic IEDs were put into the field and images have been generated for the co- and cross-polarized channel at both radar frequencies. A change detection algorithm has been applied to the data, which has been specially optimized for the application. The paper describes the experiments and discusses the detection algorithm in detail.

1 Introduction

Improvised explosive devices are currently a major threat for the forces operating in peace-enforcing missions. They are mainly positioned close to or beneath roads serving as routes for convoys. No special construction or shape is known for an IED. However, a common feature is the very high amount of explosive material capable to destroy even heavy vehicles. Typically, they are not visible at the first glance, as they are buried in the ground or hidden among non-suspicious objects. Detecting such IEDs is a counter-IED (C-IED) measure vital to secure supply routes during peacekeeping missions of the armed forces.

Millimeter-wave radars can be miniaturized in such a way that they may be used as sensors onboard of tactical UAVs. Radars operating in this section of the frequency spectrum are especially suited to detect small-scale features on the ground. Due to the wide bandwidth of the transmit signal of the radar, which can be accommodated at millimeter-wave frequencies, a high range resolution up to or even smaller than a decimeter is possible. Although penetration into the ground is not possible, indirect signatures of buried or small objects on the ground can be determined from the air.

A powerful tool to detect those IEDs is change detection between SAR images from successive flights over the same terrain. To implement a change detection algorithm, one flight has to be done sufficiently early to generate the reference scene. Shortly before the convoy is passing the route, a second flight has to be done from which the change detection algorithm can derive alarms for items present in only one of the SAR images. These alarms may be used to guide ground-penetrating radars mounted on a ground vehicle.

2 Change Detection with Millimeter-Wave SAR

The following outline describes, how we envisage to detect IEDs from change detection on SAR images:

1. During the planning phase of a convoy, conduct a first flight over the area that will be passed by the vehicles and record radar data.
   a. Construct a single, large reference image by SAR processing.
   b. Extract key regions from the reference image and store them in a database to allow for fast queries at later stages.
2. Shortly before the convoy leaves, record the same area from a tactical UAV. During the UAV flight continuously
   a. process radar data with a SAR algorithm,
   b. coarsely register each SAR stripe to the reference image by using database keys,
   c. fine-tune the registration, and
   d. calculate a change map from registered image areas.

2.1 The MEMPHIS Radar

MEMPHIS (Millimeter-wave Experimental Multi-frequency Polarimetric High-resolution Interferometric System) is a high-resolution SAR system, developed and operated by Fraunhofer FHR [1]. The radar operates simultaneously at the 35 GHz and 94 GHz radar bands, with a bandwidth of 800 MHz, using a pulsed waveform with synthetic stepped-frequency chirp. This provides a slant range resolution better than 0.2 m. MEMPHIS has four receiver channels at each of the nominal transmit frequencies of 35 GHz and 94 GHz. Depending on the antenna, they can be used for polarimetric or interferometric measurement configurations. In the polarimetric mode, right-hand (R) circular polarized pulses are sent, while co- (RR) and cross-polarization (RL) are simultaneously recorded. For the experiments discussed here, MEMPHIS was mounted onboard a C-160 Transall airplane, flying at relatively low altitude (300 m to 1000 m above ground level). The collected data typically have a swath width of 600 m, and can be up to 3 km long in flight direction. Figure 1 shows MEMPHIS onboard the C-160.

Figure 1 MEMPHIS radar onboard C-160

2.2 Image Processing on SAR data

Because flight routes differ slightly between the first and the successive flights, pixels of the recorded SAR images are not aligned between the flights and a direct image comparison is impossible. Although georeferencing performed by the Remote Sensing Lab (RSL) in Zurich is highly precise [2], a pixel-wise correspondence cannot be guaranteed. Image registration techniques are necessary to ensure direct correspondence of pixels from subsequent flights, as registration errors have proved to significantly impact the performance of change detection algorithms [3].

After images have been registered, the task of change detection is to estimate the so-called *change mask*, that holds a "set of pixels that are *significantly different"* between two images of a sequence [4]. Subtracting image intensities of two corresponding pixels and comparing the difference to a global threshold can generate this mask. Since raw SAR images contain a high level of speckle noise and different scans reflect different noise realizations, the resulting change mask is quite prone to false positives. In the literature, change detection in SAR images is typically applied to geographic mapping, where changes appear as contiguous areas. As a consequence, instead of comparing single pixels, statistical properties of pixel groups can be evaluated, resulting in an improved change mask [5]. An alternative is to first classify image regions into known types like buildings, forest, roads, etc. and then finding changes in labels [6]. Contrary to these scenarios, the changes to be detected here are very small, as IEDs are built from small parts with a diameter of two to three pixels relative to the resolution of the SAR images. This hampers detection by regional statistics. Moreover, there is not a special signature, which could be attributed to the typical IED, also there are only indirect signatures, which are sensed by the millimeter-wave radar and even more also complete different environments, like open terrain, arid or woodland, or urban terrain have to be considered as background. Therefore typical object detection methods for SAR images cannot be applied (for an overview on such methods, see [7]).

2.2.1 Fast Image Registration

Our aim is to allow for online processing of the SAR data recorded during the second flight. This requires fast registration of newly acquired images to the existing data from the first flight. During the last years, the concept of local image features has emerged as a tool for image retrieval and registration. Here, we chose to apply the SURF interest point detector and descriptor [8] that identifies salient regions in scale space. The appearances of these regions are then described by the low-dimensional SURF-36 descriptor composed of 36 values that can be used as a database key further on.

For every incoming SAR stripe, we extract SURF interest points and use their descriptors to find corresponding landmarks in the reference image. Random sample consensus (RANSAC) [9] exploits these correspondences and yields the most likely homography that aligns the input stripe with the reference image. Notice that the homography model sufficiently describes the alignment between the images since the altitude of flights is orders of magnitude larger than the height of acquired objects (buildings, trees, mountains, etc.).

2.2.2 Registration Refinement

Speckle noise in SAR images can lead to biased estimation of the locations of interest points. Hence, although RANSAC scheme rejects false positive matches, the above feature-based registration scheme provides a draft alignment and a refinement step is required towards accurate change detection results. To this end, the ECC algorithm [10] is initialized by the output of the RANSAC model estimation and exploiting all pixels of the stripes (area-based registration) provides a more stable and exact homography. We use the latter to warp the stripe and compute differences from the reference image.

2.2.3 Calculation of the Change Map

As described in the introduction, IEDs are small and their exact shape is unknown in advance. Consequently, higher order statistics cannot be employed to discriminate changed regions from background regions. Instead, we calculate the difference image of the registered SAR intensities. If registration refinement operates correctly, the noise contained in the difference image is uncorrelated between neighboring pixels [11]. Because the image content is locally correlated, spatial low-pass filtering can reduce the noise without impacting image contents. In our approach, a Gaussian low-pass filter with a small standard deviation is applied to the difference image. This has the additional advantage that the (symmetric) filter kernel is very similar to the expected small and blob-like changes and consequently the chosen low-pass filter approximates a matched filter. A similar approach is described by Weydahl, who uses a box filter to enhance small-scale changes in SAR difference images [12]. Subsequent pixel-wise comparison with a global threshold leads to a binary change map. As described by Bruzzone and Prieto, statistical dependencies of neighboring pixels can be exploited by modeling the difference image as a Markov random field (MRF) [13]. The underlying parameter estimation, however, is computationally expensive. To reduce processing costs, we chose to approximate the result by applying morphological opening to the binary change map.

3 Counter-IED Experiment

3.1 Measurement Scenario

Measurements were conducted at the training area Storkow, northeast of Berlin. To provide orientation for the pilot of the aircraft, the area was chosen to incorporate a gravel road and four marker reflectors with 360° visibility were placed at the corners of the rectangular target area. During a first flight, a SAR image was acquired without target objects on the ground to serve as a reference. After installation of eight IED-like objects, a second flight was conducted. The objects were chosen to represent typical components of IEDs, like gas canisters or anti tank mines (depicted in Figure 2) and similar small objects with a size < 0.5 m. Reflector locations were measured with a handheld GPS indicator and the placement of the target objects relative to the reflectors was assessed with a tape measure. The full geometry of placed objects in relation to the gravel road and the marker reflectors is depicted in Figure 4.

Figure 2 Photos of IED-like objects

3.2 SAR Image Quality

To test the data quality and to allow a first overview, the airborne data were processed using a quick-look SAR algorithm [14]. The resulting images have a resolution of 75 cm. Figure 3 shows reference images for both radar frequencies, 35 GHz and 94 GHz. It demonstrates, as expected from earlier measurements [15], that at 94 GHz gravel roads can be seen much more clearly, because of the enforced sensitivity for small-scale surface roughness.

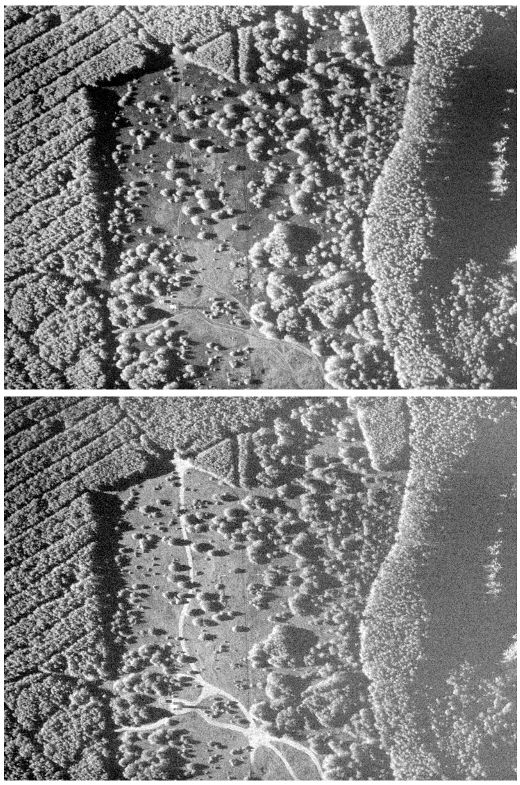

Figure 3 Cutout of SAR images at 94 GHz (above) and 35 GHz (below), co-polar channel each

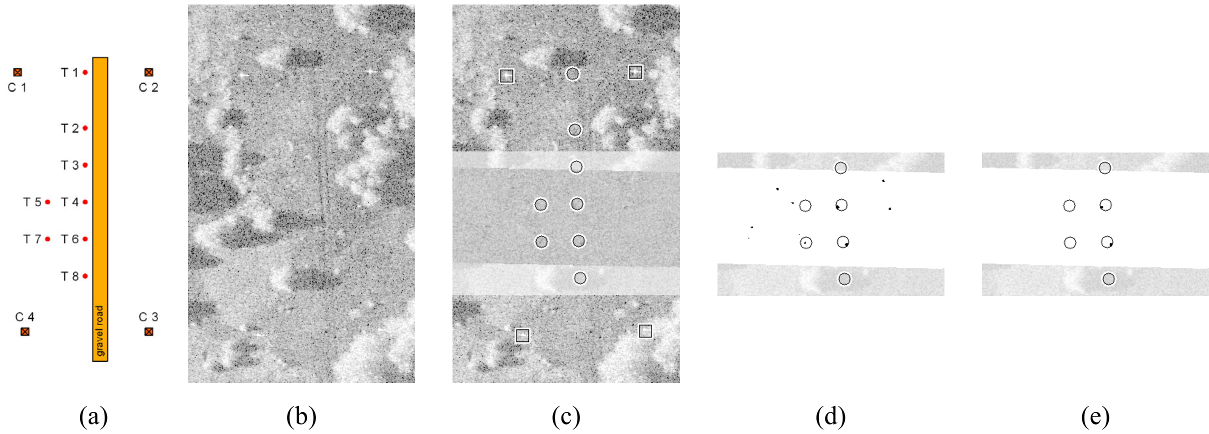

Figure 4 Target area: (a) positions of targets, (b) cutout of reference image, (c) difference of registered SAR stripe (target positions marked as circles, corner reflectors marked as squares), (d) change map, (e) change map after morphological filtering

The high-resolution SAR images were processed with the SAR algorithm developed by RSL University Zurich [16]. They serve as a basis for the change detection process.

3.3 Change Detection Results

High-resolution SAR stripes of the second flight were registered onto the first flight image according to the two-step procedure described above. Figure 4 shows the target area from the first flight with a registered single stripe of the second flight already subtracted. The binary change map shows detected changes as black dots; circles indicate the position of IED-like objects. Because of the noise contained in the SAR images, a couple of false positive changes can be found in the change map. Using a morphological opening filter, these false positives are eliminated at the cost of a true positive (see Figure 4d and 4e) getting removed as well.

Comparing radar bands and polarizations, the best ratio of detected IED-like objects versus false positives was obtained in the 35 GHz band with RR (co-polar) reception. This setup also shows the highest absolute number of correctly detected objects (see Table 1). Co-polarized channels exhibit a higher number of detected objects, which is expected, as man-made objects oftentimes possess surfaces angled at 90° that result in an even number of polarization changes.

	True positives	False positives
94 GHz RR	0 (1)	0 (12)
35 GHz RR	5 (6)	1 (> 15)
94 GHz RL	1 (2)	3 (> 20)
35 GHz RL	3 (3)	4 (> 20)

Table 1 Total number of correct detections and false alarms for the combinations of radar frequencies and polarizations. Numbers in brackets represent results without morphological post processing.

Target objects T1, T4, and T7 were visible in multiple channels, while targets T2, T3, and T6 were only visible in the 35 GHz co-polar channel.

4 Conclusions and Outlook

In this paper, we have described a novel approach to the detection of improvised explosive devices that is based on change detection from airborne synthetic aperture radar images. The proposed approach was tested on a set of eight small (diameter < 0.5 m) objects that were placed onto grassland after a reference SAR image was taken. Our change detection method is able to correctly detect five out of eight targets with two additional false alarms. Two targets were not detected in any tested radar frequency, albeit one of the targets seems to be placed in the radar shadow of nearby trees. A third target was visible in the unfiltered change maps but got removed by the closing operation because of its small size. In summary, we conclude from our experiments that it is possible to detect even small IED-like objects with millimeter-wave SAR change detection.

Because this experiment was but a first attempt to airborne IED detection, the number of tested objects is too small to confidently estimate detection rates and false alarm rates. However, as a diverse set of object types has been tested and false alarms seem reasonably few, we expect that the approach will applicable with regard to decision support in the field.

So far, no information fusion between the recorded channels was exploited. Extending our change detection algorithm to multi-channel input is expected to decrease false alarm rates.

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