Frame-Based SAR Processing and Automatic Moving Targets Parameters Extraction

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Abstract— **synthetic aperture radar is a very popular and widely used instrument for various remote sensing tasks. In the paper, we propose several novel ideas for improvement of the efficiency of the modern SAR systems. At first, the problem of the automatic image stitching is considered. Instead of the common cross-correlation based solution the local features detection and description techniques are proposed. Secondly, we analyze the problem of the moving target parameters estimation. It is shown that the optical flow techniques can be used for the automatic extraction of the moving target shifts from the sequence of SAR looks. Experimental examples with real SAR data are illustrated and comprehensively discussed.**

Keywords—synthetic aperture radar, image stitching, keypoint descriptors, moving targets, optical flow

I. INTRODUCTION

A rapid development of novel hardware and software solutions opens a way for creation of the next generation radar systems [1]-[2]. A good tool of choice is the well-known synthetic aperture radar (SAR). Such radar system provides the high-resolution images of the Earth surface [3]-[6] in all weather and lighting conditions. One of the goals is to make the SAR almost fully automatic. This is achievable via the incorporation of the intelligent signal and image analysis techniques.

In the paper, we demonstrate two examples of how the advanced computer vision [7] techniques can be applied in the SAR image formation and analysis problems. At first, the problem of the SAR panorama stitching is considered. It is shown that the usage of the keypoint descriptors allows to perform the automatic frame-based SAR processing without the information about SAR platform orientation. Secondly, the problem of the moving targets analysis [8]-[10] is examined. It is known, that the moving targets are appeared as shifted and defocused in the resulting SAR images. In the case of the multi-look processing this can lead to significant defocusing [11]. In this study we propose to utilize the optical flow techniques [7] for the automatic target shifts estimation.

In Section II the peculiarities of the frame-based SAR processing are described. The key features of the speeded up robust features (SURF) algorithm [7], [12] are considered. Section III contains the experimental examples of how the Lucas-Kanade optical flow algorithm [7] is used for the automatic estimation of the moving target displacements from the sequence of SAR looks. Experimental examples with real SAR images obtained with the RIAN-SAR-X system [13] are analyzed as well.

II. IMAGE FORMATION AND STITCHING

From the signal processing point of view, SAR image formation is equivalent to the two-dimensional data compression [6]. The focusing in the range direction is a straightforward process accomplished by using a specific waveforms [3]-[6]. As for the azimuth direction, the aperture synthesis is performed based on the SAR platform movement [6]. A well-known problem here is an unstable SAR platform motion leading to the significant image quality degradation [3]-[4], [11]. The common solution in this case is the trajectory measurement via the radar navigation system with subsequent motion compensation procedure [4], [6]. In the case of high-resolution imaging, additional application of the autofocusing techniques is necessary [4], [14]-[15].

The most popular SAR image formation methods are so-called block-based (frame-based) algorithms [6]. In particular, the range-Doppler algorithm (RDA). The main advantages of the method are speed (due to the fast Fourier transform application) and simplicity of implementation. According to such approach, the SAR raw data are processed consequently frame-by-frame (Fig. 1)

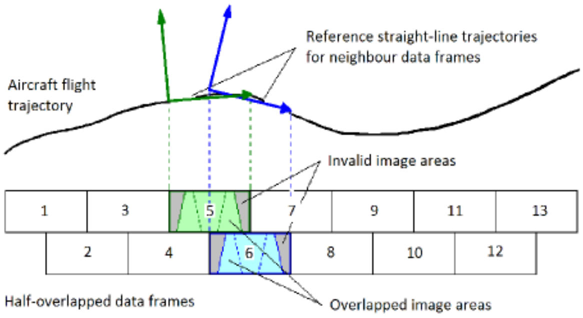

Figure 1. SAR processing in frame basis.

Since the light-weight platforms are quite unstable and both local deviations and orientation instabilities significantly affects on the image formation, each SAR frame is

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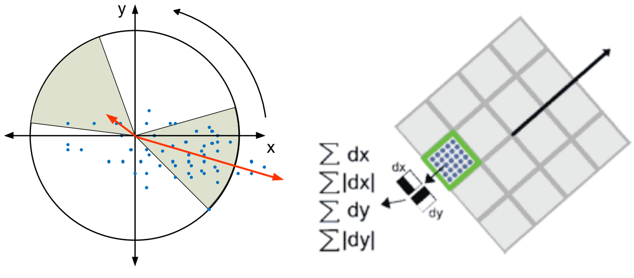
processed with its own reference trajectory. In order do not loose the information, we apply the half-overlapping scheme.

Obviously, that the problem of the image stitching arises in this case. A common solution is to use the two-dimensional cross-correlation of the adjacent SAR frames. One should emphasize that the relative frames orientation is measured via the navigation system (it is defined via the platform velocity vector). In order to make the SAR panorama stitching automatic, we have utilized the SURF algorithm. The approach is widely used in the object detection and recognition, tracking and image stitching [7], [12]. The main steps of SURF are keypoint detection, description and matching. At first, according to the scale-space analysis [16], the Hessian matrix is calculated for each scale σ

$$H(x,y,\sigma)=\begin{bmatrix} L_{xx}(x,y,\sigma) & L_{xy}(x,y,\sigma) \\ L_{xy}(x,y,\sigma) & L_{yy}(x,y,\sigma) \end{bmatrix}, \qquad (1)$$

where each matrix element is the convolution of input image $I(x,y)$ with corresponding second order derivative of Gaussian $g(\sigma)$. For higher efficiency, such derivatives are approximated via box filters in SURF algorithm. As a result, keypoints could be found quite fast. More details about keypoint detection can be found in [12].

Next important steps are keypoint orientation assignment and SURF descriptor construction (Fig. 2)



(a) (b)

Figure 2. SURF keypoint orientation and descriptor construction (a – orientation assignment, b – descriptor construction).

The keypoint orientation is estimated via analysis of circular neighborhood around its location. A set of Gaussian weighted Haar wavelet responses [17] are calculated. Resulting values are mapped on Cartesian grid, where horizontal and vertical response strengths are located along x and y axis respectively (blue points in Fig. 2a). The dominant orientations are estimated by calculating the sum of all responses within a sliding orientation window of size $\pi/3$. The window position with maximum total response corresponds to the keypoint orientation (the longest red arrow in Fig. 2a).

After keypoint orientation estimation, we are ready to construct the SURF descriptor. The rectangular area with size $20s$ (s is a keypoint scale) is considered with respect to keypoint orientation (Fig. 2b). The whole window is divided in 4*4 quadrants and a set of 4D vectors are constructed for each quadrant. Elements of such vector are calculated as Haar wavelet responses

$$\sum d_x, \sum d_y, \sum |d_x|, \sum |d_y|,$$

where summation is performed for 25 sampling points in each quadrant. As a result, 64-dimensional SURF descriptor is constructed.

The next step is the matching of descriptors. The matching score is determined as the Euclidean distance as follows

$$l_E=\left(\sum_{i=1}^{64}(u_i-v_i)^2\right)^{1/2}, \qquad (2)$$

where u_i, v_i are corresponding elements of keypoints descriptors. Due to the speckle noise in SAR images, straightforward descriptors matching can lead to errors in the image stitching. In order to increase the efficiency, we have rejected the repeated descriptors and set the distance threshold $l_E \le l_E^{th}$. Fig. 3 illustrates an example of matched pairs of keypoints after filtration.

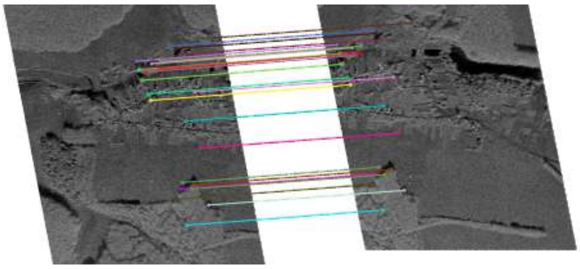


Figure 3. Matched pairs of keypoints.

The final step is the reconstruction of the affine matrix. It is known that 3 keypoints correspondence is enough for the determination of both rotation and translation components. An alternative way is to apply the least-squares fit into the full sequence of the keypoint pairs. Thus, the frames stitching can be done only based on image analysis techniques.

III. MOVING TARGETS ANALYSIS

The moving targets analysis is a popular research direction in the SAR community. In addition to a common moving target indication (MTI), the estimation of the full information about the moving objects is an important task.

The challenge is that in the case of the single-antenna SAR system the target velocity/location ambiguity appears [10]. It was shown that for unambiguous extraction of the moving target trajectory two things should be known: the target positions in the sequence of the SAR looks and the road locations within the SAR image. The coordinates of the road segments can be detected using the analysis of the edge map and local gradients of the multi-look SAR images [10]. In order to make the method to be fully automatic, we propose to utilize the optical flow (OF) methods [7]. These techniques were successfully applied for the ice motion estimation [18] and image co-registration [19]. In the paper, we propose to utilize the modified version of the Lucas-Kanade optical flow algorithm.

According to the definition, the OF is the apparent motion of the image objects between two consecutive frames (video frames in optical band). In our consideration two adjacent SAR looks can be used for the analysis in similar way.

The main assumption of the OF methods is the intensity preservation during the movement of the object pixel. In such ideal situation this can be written in the following way

$$I_{iL}(x,y,t) = I_{iL+1}(x+dx, y+dy, t+dt), \qquad (3)$$

where (x,y) is the pixel coordinates, $iL, iL+1$ are indexes of adjacent SAR looks. Since the time of synthesis is typically quite small [14], the value of dt corresponds to the fractions of the second. Expanding (3) into the Taylor series gives the simple equation

$$I_x u + I_y v + I_t = 0, \qquad (4)$$

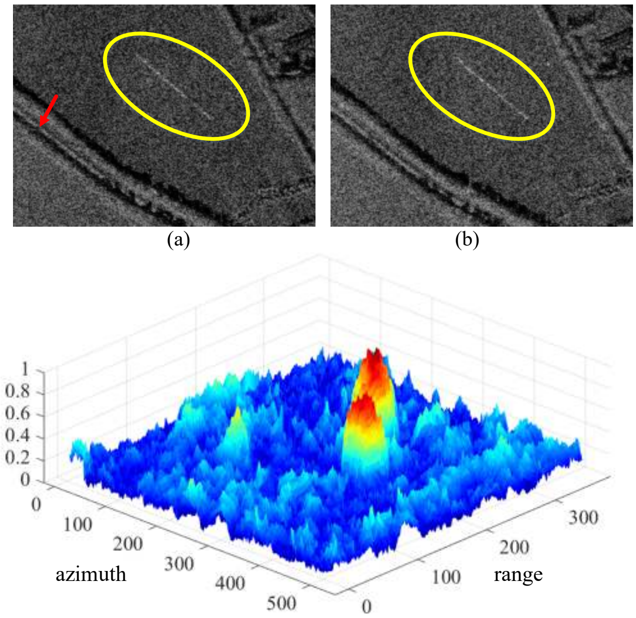
where I_x, I_y are the spatial gradients of the image, $I_t = I_{iL+1} - I_{iL}$, $u = dx/dt, v = dy/dt$. Since we have two unknowns, it is impossible to solve (4) for a single pixel. Therefore, according to the Lucas-Kanade method, the OF is considered to be the same within the local pixel neighborhood. This idea allows to construct the set of equations within the local image patch

$$\begin{bmatrix} \sum I_x^2 & \sum I_x I_y \\ \sum I_y I_x & \sum I_y^2 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = -\begin{bmatrix} \sum I_x I_t \\ \sum I_y I_t \end{bmatrix}. \qquad (5)$$

Here the summation is performed within a specified spatial window around a chosen point. Thus, the OF can be separately estimated for the chosen set of image pixels. It is often the image corners are detected for this purpose [7].

The challenge is that the main assumption of the pixels intensity preservation is not held in the case of SAR images. The reason is the existence of the speckle noise. This may lead to the false detections. In our consideration, two single-look SAR images are used as input for the OF analysis. Fig. 4 illustrates an example of two SAR looks (1m resolution) and surface plot of the estimated OF. In Fig. 4a the railroad is indicated by a red arrow. The train appears beyond it (yellow ellipse). The optical flow surface is shown Fig. 4c. One can observe multiple local peaks. Two peaks correspond to the moving train. Other peaks in Fig. 4c are caused by the existence of the speckle noise and the movement of the trees due to the wind. Also the amplitudes of pixels in SAR looks are modulated by the real antenna pattern, which affects on images histograms as well. Obviously, this may lead to false detections.

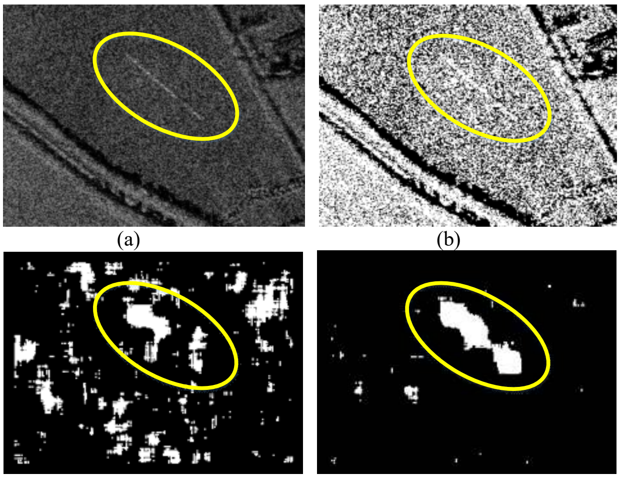
It is known that in order to extract the moving target parameters, its location on SAR looks pair (x_n, y_n), (x_m, y_m) should be known [10]. Fortunately, such positions can be detected automatically using optical flow.



(c)

Figure 4. Optical flow calculation
(a – first SAR look, b – second SAR look, c – optical flow surface).

Let's consider an example of a single-look SAR image with moving train (Fig. 5a). It is very difficult to detect it directly. Fig. 5b contains the same SAR look after the application of the constant binary threshold. One can see that the target of interest is contaminated by the noise. In order to detect the moving train, the estimated OF magnitude image can be used. The application of thresholding in this case results in the image shown in Fig. 5c.One can observe a lot of blobs of different size. In order to increase the efficiency, two important steps are applied. At first, the histograms of both SAR looks are adjusted according to the histogram of



(c)
(d)

Figure 5. Example of moving train detection using optical flow
(a – SAR image, b – SAR image after binarization,
c – OF binary image, d – OF binary image with preprocessing).

the multi-look image. We have found that in this case the result is better than in the case of direct histogram adjustment of two single-look images. Secondly, the speckle filtering is performed [20]. Fig. 5d illustrates the binary image of the OF magnitude with application of described preprocessing. One can observe that the blob corresponding to the train is clearly seen. Thus, the moving object is detected using the OF magnitude image. One should emphasize that the target blob in the second image can be found in the similar way using the reverse OF estimation. Since the real targets commonly have complex shapes, an approximate locations in SAR looks (x_n, y_n) can be estimated as the mass centers of the corresponding blobs

$$x_n^C = \frac{\sum_x \sum_y x I(x,y)}{\sum_x \sum_y I(x,y)}, \; y_n^C = \frac{\sum_x \sum_y y I(x,y)}{\sum_x \sum_y I(x,y)}, \quad (6)$$

where the summation is performed within the blob area.

Developed method for the automatic target shift estimation represents a good contribution to the new generation radar systems. All demonstrated SAR images were obtained with the airborne RIAN-SAR-X system [13] produced at the Institute of Radio Astronomy.

IV. CONCLUSION

In the paper, we have proposed two ideas of how to use the advanced image analysis techniques in SAR processing problems. At first, it was shown that incorporation of local keypoint descriptors allows to perform the SAR image panorama stitching without any information about the platform orientation. Secondly, we have integrated the Lucas-Kanade optical flow algorithm for the estimation of the moving target positions from the sequence of single-look SAR images. Proposed approach can be used for automatic moving target parameters estimation with a single-antenna SAR system.

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