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A SAR ATR Algorithm Based on Coherent Change Detection

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A SAR ATR Algorithm Based on Coherent Change Detection

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Abstract

This report discusses an automatic target recognition (ATR) algorithm for synthetic aperture radar (SAR) imagery that is based on coherent change detection techniques. The algorithm relies on templates created from training data to identify targets. Objects are identified or rejected as targets by comparing their SAR signatures with templates using the same complex correlation scheme developed for coherent change detection. Preliminary results are presented in addition to future recommendations.

Acknowledgments

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Nomenclature

ATR	automatic target recognition
CID	complex identification
CoCD	coherent change detection
DARPA	Defense Advanced Research Project Agency
LDRD	laboratory directed research and development

Introduction

This report documents efforts conducted under the Laboratory Directed Research and Development (LDRD) project "ATR/Exploitation Utilizing Ultra-High Resolution, Complex SAR Imaging". The focus of this research was to develop automatic target recognition (ATR) techniques that exploit the capabilities of advanced synthetic aperture radar (SAR) sensors. Existing ATR algorithms typically work with just magnitude SAR data at resolutions of 0.3 meters or more. Algorithms examined here utilize complex (magnitude and phase) data at resolutions less than 0.3 meters.

At the beginning of this project, ultra-high resolution SAR imagery was not readily available. Consequently, a significant part of the work consisted of obtaining the required data. In March of 1998, over 1400 images were collected using a Sandia Ka-band radar with a resolution of 0.051 meters. Target vehicles in the scene consisted of two M-113 personnel transports, two HMMWV trucks, one T-62 tank and one T-72 tank. A second more extensive data collection was also carried out in June of 1999. Over 3000 images and 70 km² of clutter were obtained using a Sandia test-bed Ku-band radar with a resolution of 0.10 meters. Two SCUD missile launchers, two T-72 tanks, and one T-62 tank were the vehicles in the scene. Figure 1 shows photographs of target vehicles from both data collections.

Several methods for exploiting complex data were analyzed during this program. These include phase feature extraction, inverse scattering, sub-aperture processing, and coherent change detection. Phase feature extraction examined an approach advocated by Rihaczek (Rihaczek and Hershkowitz 1996) for categorizing peaks by their phase characteristics. This approach was abandoned early on when preliminary analysis indicated it would not be useful. The inverse scattering method relied on a model of the electromagnetic interactions to extract target shape information. Inverse scattering techniques are notoriously ill-posed and a key part of the method was a modification of regularization techniques developed for inverse acoustic scattering (Colton and Kress 1998). Unfortunately, there was not sufficient time to implement this approach and therefore its usefulness could not be evaluated. Sub-aperture processing was employed to analyze peak stability and to resample high-resolution images to lower resolutions. An interesting result of the work was that in some situations, analyzing the movement of peaks across sub-apertures reveals surface curvature of the target. Sub-aperture processing also demonstrated potential for suppressing clutter.

The remainder of this report describes the coherent identification (CID) algorithm that is based on coherent change detection techniques (Jakowatz et al. 1996). Coherent change detection (CoCD) is a powerful method developed to highlight subtle changes between SAR images. The challenge for applying CoCD to an ATR algorithm is adjusting the sensitivity so that different serial numbers and configurations of a target can still be recognized without accepting false alarms. Initial results from both the sub-aperture processing and CID approaches led to additional funding from the Defense Advanced Research Project Agency (DARPA). Sandia Report SAND2000-2101 by K. M. Simonson discusses some of this DARPA work.

HMMWV, Ka Collection

HMMWV, Ka Collection

M-113, Ka Collection

T-62, Ka & Ku Collections

T-72 #877, Ka & Ku Collections

T-72 #803, Ku Collection

SCUD, Ku Collection

Figure 1. Ka & Ku Data Collection Vehicles

CID Overview

Following the success of other Sandia ATR algorithms, the CID algorithm relies on templates created from training data to identify targets. Objects are identified or rejected as targets by comparing their SAR signatures with a template. The test statistic used in CID is the same one developed for CoCD:

$$\alpha_{ij} = \frac{\left| \sum_{n=-w}^w \sum_{m=-w}^w T_{i+m,j+n}^* P_{i+m,j+n} \right|}{\sqrt{\left(\sum_{n=-w}^w \sum_{m=-w}^w |T_{i+m,j+n}|^2 \right) \left(\sum_{n=-w}^w \sum_{m=-w}^w |P_{i+m,j+n}|^2 \right)}}$$

where T_{ij}^* is the complex conjugate of a template pixel and p_{ij} is a test image pixel. The summations are over small windows (e.g., 3x3, 5x5) surrounding pixel ij . Image pixels strongly correlated with the template have $\alpha_{ij} \approx 1$ and pixels unlike the template have $\alpha_{ij} \approx 0$. A target is declared if enough pixels in the template correlate with the image. The level of correlation and number of pixels required to identify a target are determined in the training process.

Alignment Process

The performance of CID is critically dependent on the alignment of the template and test chip. In general, interferometric image comparisons require sub-pixel alignment. For CID this is done in four steps. The first step obtains coarse, pixel-level, estimates of translation differences between the template and test chip. The second step then refines these estimates to sub-pixel levels and simultaneously corrects for rotations. Both of these steps ignore phase information and operate on just magnitude data. Conversely, the third and fourth steps of the alignment process concentrate on just the phase data. The phase adjustment steps follow the same organization as the magnitude alignment. The third step does a course phase error estimate followed by refinements in the fourth step. Details of the four alignment steps are discussed below.

The course magnitude alignment starts by finding integer translations m,n that maximize the correlation expression

$$C_{mn} = \sum_{i=1}^I \sum_{j=1}^J |T_{ij}| |P_{i-m,j-n}|$$

where the summations are over all non-zero template pixels. The translations are found by simply varying m,n and looking for the largest C_{mn} . Since templates are usually valid over some small (e.g., $\pm 2.5^\circ$) aspect angle range, course rotation angle estimates are simply taken to be the template design angle.

Sub-pixel refinements to the translation and rotation estimates are determined from

$$S(\vartheta, \mathbf{a}) = \sum_{i=1}^I \sum_{j=1}^J |T_{ij}| |p(\mathbf{R}(\vartheta) \mathbf{x}_{ij} - \mathbf{a})|$$

where

$$\mathbf{x}_{ij} = \begin{pmatrix} i \\ j \end{pmatrix}, \quad \mathbf{a} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \quad \text{and} \quad R(\vartheta) = \begin{pmatrix} \cos \vartheta & -\sin \vartheta \\ \sin \vartheta & \cos \vartheta \end{pmatrix}$$

In the expression for $S(\vartheta, \mathbf{a})$, discrete pixels p_{ij} are now represented by a continuous function $p(\mathbf{R}(\vartheta) \mathbf{x}_{ij} - \mathbf{a})$. The function is created from the test chip using a two-dimensional spline interpolation. The sub-pixel rotation angle ϑ and displacement vector $\mathbf{a}$ are found simultaneously using an iterative Levenberg-Marquardt (Press et al. 1992) algorithm to maximize S . Starting values for the iterations come from the course solutions: $\vartheta = \theta$, and $\mathbf{a} = (m, n)^T$.

After aligning the test chip and template magnitudes, phase errors must be minimized. This is accomplished by minimizing the expression:

$$G(\varphi, \mathbf{k}) = N - \sum_{n=1}^N \cos(\Phi_n - \phi_n - \varphi - \mathbf{k} \cdot \mathbf{x}_n)$$

where N is the number of template phase pixels, Φ_n is the template phase, ϕ_n is the test chip phase, and $\mathbf{x}_n = (i_n, j_n)$ is the two-dimensional location of pixel n . The phase errors φ and $\mathbf{k} = (k_1, k_2)$ are estimated through a similar process as the rotation and translation errors. Approximate values are found through a brute-force search and then refined by a Levenberg-Marquardt algorithm that minimizes G .

The pixels used in estimating phase errors are a subset of those used in magnitude alignment. Some magnitude pixels are eliminated if their phase is questionable. These points are identified by performing a line integral of the phase difference around a pixel. In particular, the expression

$$Q_{ij} = \text{atan2}(\sin(\phi_{i+1j} - \phi_{ij}), \cos(\phi_{i+1j} - \phi_{ij})) + \text{atan2}(\sin(\phi_{i+1j+1} - \phi_{i+1j}), \cos(\phi_{i+1j+1} - \phi_{i+1j})) + \\ \text{atan2}(\sin(\phi_{ij+1} - \phi_{i+1j+1}), \cos(\phi_{ij+1} - \phi_{i+1j+1})) + \text{atan2}(\sin(\phi_{ij} - \phi_{ij+1}), \cos(\phi_{ij} - \phi_{ij+1}))$$

is evaluated for each pixel. Pixels with $Q_{ij} \neq 0$ are dropped from the phase error estimation since they may be confounded with layover effects. These are the same pixels that cause difficulties unwrapping phase (Ghiglia and Pritt 1998).

One final point that needs to be mentioned is that all of the alignment is done in the ground plane. Since Sandia radars form images in the slant plane (Carrara et al. 1995), target chips are first transformed to the ground plane to eliminate range foreshortening. This improves rotational alignment because the physical dimensions of the target are correct in the ground plane. An alternative approach could still use the slant plane, but an estimate of the range foreshortening would need to be calculated.

Template Generation

Template generation for most of the Sandia ATR algorithms starts by dividing a set of target chips into different groups covering a range of aspect and depression angles. Typical ranges are $\pm 2.5^\circ$ in aspect and $\pm 1^\circ$ in depression; covering a full 360° in aspect then requires 72 templates. Next, target chips in each angle group are aligned and combined into a mean chip representative of the group. Finally, a template mask is formed by extracting regions of the mean chip characteristic of the target signature (e.g., bright specular and dark shadow areas). The template mask for CID is generated by a simple spot-growing algorithm. The brightest pixel on the target serves as the starting point and additional pixels are added at each successive brightness level. The process continues until a specified number of pixels are in the mask. CID templates are therefore "bright-only" masks.

Figure 2 is a flow chart showing the CID template design process. The goal is to develop a template that gives the best coherent correlation score over all the design chips. Starting with an angle group of N target chips, each chip is treated in turn as the basis for a template mask. The chip having the best average correlation with all the other chips serves as the reference chip. Each of the remaining $N-1$ chips is then combined with the reference chip to form $N-1$ means composed of two chips. The two-chip mean with the highest average correlation then serves as the starting point for creating three-chip means from the remaining $N-2$ chips. This process continues until all chips have been added to the mean. The combination of chips giving the best average correlation over all the design chips is retained as the template mean. Unfortunately, there are no guarantees this *ad hoc* approach produces the best template. At most, it creates a template that is locally optimal but not necessarily globally optimal over all possible chip combinations. More work is needed to improve the template design process.

In a manner similar to the alignment process, the template mean is created by separately combining the magnitudes and phases of the individual chips. The mean magnitude $|T_{ij}|$ comes from the mean of the N chip magnitudes ($|p_{ijn}|$ for the n th chip),

$$|T_{ij}| = \frac{1}{N} \sum_n |p_{ijn}|$$

and the mean phase Φ_{ij} is calculated as a vector sum of the phases ϕ_{ijn} of the individual chips,

$$\Phi_{ij} = \tan^{-1} \left(\frac{\sum_n \sin(\phi_{ijn})}{\sum_n \cos(\phi_{ijn})} \right)$$

Figure 2. Template Design Process

Figure 3. T-72 (#877) Template Design Chips

As an example of the template generation process, consider the chips shown in Figure 3. These are design chips for a T-72 tank (serial number 877) with a depression of 30° , aspects of $60^\circ \pm 2.5^\circ$, and a resolution of 0.1 meters. The chips surrounded by red boxes were ultimately not used to create the template. The best average correlation over all the chips was obtained using just those surrounded by blue and green boxes. The blue box identifies the reference chip having the best correlation with all of the other chips. The template mean and mask made from the green and blue chips are shown in Figure 4. The "Swiss cheese" appearance of the mask comes from the phase consistency check described earlier that excludes some bright points.

Figure 4. T-72 Template Mean and Mask

Figure 5. Template Correlation Results

Results

Figure 5 presents results of correlating the 60° T-72 template from the last section with several chips. The lower row consists of the correlation maps with dark areas indicating small α values and therefore weak correlation. The numbers below the maps indicate the average correlation with the template. These examples represent typical results. Figure 6 shows pixel probability distributions over a more complete set of 60° test chips and clutter. With a detection probability of 100%, four false alarms occurred in 26 km² (false alarm rate of 0.153 km⁻²) and no false alarms occurred at a detection probability of 93% (false alarm rate < 0.0382 km⁻²).

Unfortunately, there was insufficient time to completely evaluate the CID algorithm and consequently many important questions are left unanswered. Limited testing performed to date indicates CID templates should probably be trained over smaller angle ranges than other magnitude-only algorithms. Image level coherent change detection usually requires angle differences no more than $\pm 0.5^\circ$. Fortunately, manmade targets correlate over a wider range; however, the optimum range for CID templates still needs to be determined. One surprising result of the preliminary testing is that the CID algorithm performance does not appear to be strongly dependent on resolution.

A significant open question concerns CID robustness. The pixel probability distributions in Figure 6 show that templates trained on one model of T-72 with grenade launchers and fuel drums (#877) are able to reject another model of T-72 (#803) without these features. Although this can be a desirable algorithm characteristic for vehicle "fingerprinting", it

Figure 6. Pixel Probability Distributions

would not be desirable for a general ATR system designed to find arbitrary T-72 tanks. Testing still needs to be done to assess CID performance with templates trained on both T-72 models. Figures 7 and 8 provide evidence that CID has some tolerance for image quality and vehicle variability. Figure 7 shows a blurred T-62 tank and the resulting correlation map with a T-62 template. Figure 8 shows a correlation map for a T-62 in a different configuration. One turret hatch and several equipment boxes on the left side were opened and an engine cover at the rear was removed. As can be seen, in both examples there is good correlation.

In conclusion, the CID algorithm has demonstrated the ability to identify targets and reject both clutter and confusing vehicles; however, additional testing is needed to fully assess the algorithm's overall usefulness.

Figure 7. Blurred T-62 Chip, 0.599 Correlation

Figure 8. Modified T-62, 0.664 Correlation

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