Geometrical and Magnitude Invariants for Recognition of Articulated and Non-standard Objects in MSTAR Images

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Abstract
Using SAR scattering center locations and magnitudes as features, invariances with articulation (i.e. turret rotation for the T72 tank and ZSU 23/4 gun), with configuration variants (e.g. fuel barrels, searchlights, wire cables, etc.) and with a depression angle change are shown for real SAR images obtained from the MSTAR public data. This location and magnitude quasi-invariance is used as a basis for an innovative SAR recognition engine that successfully identified real articulated and non-standard configuration vehicles based on non-articulated, standard recognition models. Identification performance results are given as confusion matrices and ROC curves for articulated objects, for configuration variants, and for a small change in depression angle with the MSTAR data. The recognition rate is related to the percent of location and magnitude invariant scattering centers.

1 Introduction
In this paper we are concerned with the problem of recognizing articulated vehicles and actual vehicle configuration variants in real SAR images. Our previous work in this area (see [1][2]) used the location invariance of scattering centers and was primarily based on simulated SAR data.

The key contributions of this paper are:

1. Demonstrates that quasi-invariant scattering center locations exist and that their magnitudes are also quasi-invariant for (a) articulation; (b) configuration variants; and (c) a depression angle change for actual vehicles in real SAR data.

2. Develops a new recognition engine based on scattering center location and magnitude features that achieves significant vehicle recognition performance for articulation, configuration variants and depression angle changes with real SAR data.

2 Scatterer Location Invariance
The relative locations of SAR scattering centers, determined from local peaks in the radar return, are related to the aspect and physical geometry of the object, independent of translation and serve as distinguishing features. A photo image of a typical MSTAR target, T72 tank serial number (#) a64, is shown in Figure 1. Regions of interest (ROI) are found in the MSTAR SAR target chips (as outlined in [1]) and the scattering centers are extracted from the SAR magnitude data (within the boundary contour of the ROI) by finding local eight-neighbor maxima. Example SAR image and the regions of interest (ROI), with the locations of the scattering centers superimposed, are shown in Figure 2 for baseline and articulated versions of the T72. Because the object and ROI are not registered, we express the scattering center location invariance with respect to articulation, configuration differences or depression angle changes as the maximum number of corresponding scattering centers (whose locations match within a stated tolerance) for the optimum integer pixel translation.

Given an original version of a SAR target image with n scattering centers, represented by points at pixel locations $P_i = (x_i, y_i)$ for $1 \leq i \leq n$ and a translated, distorted version $P'_j = (x'_j, y'_j)$ $(1 \leq j \leq n)$ at a translation $t = (t_x, t_y)$, we define a match between points $P'_j$ and $P_i$ as:

$$M_{ij}(t) = \begin{cases} 1 & \text{if } |x'_j - t_x - x_i| \leq l \text{ and } |y'_j - t_y - y_i| \leq l \\ 0 & \text{otherwise} \end{cases}$$

where $l = 0$ for an 'exact' match and $l = 1$ for a match 'within one pixel'.

The scatterer location invariance, $\Lambda_{ij}$ of $n$ scatterers, expressed as a percentage of matching points, is
given by:

\[ L_n = \max_i \left\{ \frac{100}{n} \sum_k \min \left( \sum_{j=1}^n M_{ij}(t), 1 \right) \right\} \]

where each point \( f_j \) is restricted to at most one match.

Figure 3 shows the location invariance, \( L_n \), of the strongest 40 scattering centers with articulation for MSTAR T72 #a64 (at a 30° depression angle) as a function of the hull azimuth. The average invariance is 17.2% for an exact match of scattering centers and 57.8% for a location match within a one pixel (3x3 neighborhood) tolerance. Similarly, Figure 4 shows the percent of the strongest 40 scattering center locations that are invariant for T72 #a812 vs. #132 (at a 15° depression angle). Figure 5 shows the percent scattering center location invariance for T72 #132 at 17° vs. 15° depression angles. The mean and standard deviation for percent location invariance (for 40 scatterers, and depression angle 9°) are shown in Table 1 for articulated versions of the T72 and ZSU23/4, for configuration variants of the T72 and BMP2 and for depression angle changes with the T72 and BMP2.

3 Scatterer Magnitude Invariance

Using a scaled scatterer amplitude (S), expressed as a radar cross section in square meters, given by

\[ S = 100 \log_{10} (i^2 + q^2) \]

where \( i \) and \( q \) are the components of the complex radar return, we define a percent amplitude change (\( A_p \)) as:

\[ A_p = \frac{100(S_j - S_i)}{S_i} \]  

This form allows a larger variation for the stronger signal returns. A location and magnitude match \( Q_{AM}(i) \) is given by:

\[ Q_{AM}(i) = \begin{cases} 1 & \text{if } M_{ij}(t) = 1 \text{ and } |A_p| \leq L_A \cr 0 & \text{otherwise} \end{cases} \]

where \( L_A \) is the percent amplitude change tolerance. The scatterer magnitude and location invariance, \( L_{AM} \), expressed as a percentage of \( n \) scatterers, is given by:

\[ L_{AM} = \max_i \left\{ \frac{100}{n} \sum_k \min \left( \sum_{j=1}^n Q_{AM}(t), 1 \right) \right\} \]

Figure 6 shows the probability mass functions (PMFs) for percent amplitude change for the strongest 40 articulated vs. non-articulated scattering centers of T72 tank #a64. Curves are shown for the cases where the scattering center locations correspond within a one pixel tolerance and for all the combinations of scatterers whose locations do not match. For the cases with locations that matched within 1 pixel, the percent amplitude change mean and standard deviation are 0.51 and 5.91, while the non-matching cases are 0.75 and 10.44, respectively. The crossover points of the two curves are at -5 and +6 percent. Similarly, Figure 7 shows the PMFs for percent amplitude change for the strongest 40 scattering centers of T72 #a812 vs. #132 (at a 15° depression angle), while Figure 8 shows this for 17° vs. 15° depression angle (for T72 #132). The mean and standard deviation for these matching and non-matching scatterers and the crossover points for the PMFs are given in Table 2. Table 3 shows the mean and standard deviation for the percent location and magnitude invariance (within a 1 pixel location tolerance and an amplitude change tolerance of \( L_A \)) of the strongest 40 scatterers for these same articulation, configuration difference and depression angle change cases.

4 SAR Recognition Engine

Our new 6D model-based SAR recognition engine (the original 2D version is described in detail in [2]) uses standard non-articulated models of the objects.
Table 3: Scatterer percent location and magnitude invariance (for locations within one pixel and amplitude tolerance $\delta_a$).

<table>
<thead>
<tr>
<th>Percentage change</th>
<th>$\delta_a$</th>
<th>mean</th>
<th>s. d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>articularation:</td>
<td>T22 #648</td>
<td>±9</td>
<td>53.47</td>
</tr>
<tr>
<td></td>
<td>ZSU #608</td>
<td>±9</td>
<td>47.98</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td></td>
<td>50.78</td>
</tr>
<tr>
<td>configuration variants:</td>
<td>T22: #412 vs #312</td>
<td>±9</td>
<td>45.40</td>
</tr>
<tr>
<td></td>
<td>#67 vs #312</td>
<td>±9</td>
<td>50.69</td>
</tr>
<tr>
<td></td>
<td>BMP2: #9563 vs #21</td>
<td>±9</td>
<td>54.38</td>
</tr>
<tr>
<td></td>
<td>#9566 vs #21</td>
<td>±9</td>
<td>53.00</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td></td>
<td>51.68</td>
</tr>
</tbody>
</table>

1. For each model Object do 2
2. For each model Articularation do 3, 4, 5
3. Obtain the location $(R, C)$ and magnitude $(S)$ of the strongest $M$ scatterers.
4. Order $(R, C, S)$ triples by descending $S$.
5. For each model $O$ from 1 to $M$ do 6
6. For each point $P$ from $O+1$ to $M$ do 7, 8
7. $dR = R_P - R_O$, $dC = C_P - C_O$.

Table 2: Scatterer percent amplitude change.

<table>
<thead>
<tr>
<th>Percentage change</th>
<th>within 1 pixel</th>
<th>no match</th>
<th>mean</th>
<th>s. d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>articularation:</td>
<td>T22 #648</td>
<td>±9</td>
<td>3.48</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>ZSU #608</td>
<td>±9</td>
<td>7.93</td>
<td>3.64</td>
</tr>
<tr>
<td>configuration variants:</td>
<td>T22: #412 vs #312</td>
<td>±9</td>
<td>7.39</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td>#67 vs #312</td>
<td>±9</td>
<td>5.69</td>
<td>2.20</td>
</tr>
<tr>
<td></td>
<td>BMP2: #9563 vs #21</td>
<td>±9</td>
<td>5.72</td>
<td>1.94</td>
</tr>
<tr>
<td></td>
<td>#9566 vs #21</td>
<td>±9</td>
<td>5.38</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td></td>
<td>5.73</td>
<td></td>
</tr>
</tbody>
</table>

1. Obtain from test image the location $(R, C)$ and magnitude $(S)$ of $M$ strongest scatterers.
2. Order $(R, C, S)$ triples by descending $S$.
3. For each origin $O$ from 1 to $M$ do 4
4. For each point $P$ from $O+1$ to $M$ do 5, 6
5. $dR = R_P - R_O$, $dC = C_P - C_O$.
6. For $dR$ from $dR-1$ to $dR+1$ do 7
7. For $dC$ from $dC-1$ to $dC+1$ do 8, 9, 10
8. weighted vote = $[dR + dC]$
9. Look up list of model entries at $dR, dC$.
10. For each model entry $E$ in the list do 11
11. IF $tr = R_E - R_O < \text{translation limit}$ and $tc = C_E - C_O < \text{translation limit}$ and $|1 - S_E/S_O| < \text{magnitude limit}$ and $|1 - S_E/S_O| < \text{magnitude limit}$ then increment accumulator array (Object, Articularation, $tr$, $tc$) by weighted vote.
12. Query accumulator array for each Object, Articularation, $tr$ and $tc$, summing the votes in a 3x3 neighborhood in translation space about $tr$, $tc$; record the maximum vote, sum and the Corresponding Object.
13. IF maximum vote, sum > threshold THEN results are model ELSE result is "unknown".

Figure 9: Model construction algorithm

The recognition process is an efficient search for positive evidence, using relative locations of scatterer centers to access the look-up table and generate votes for the appropriate object, azimuth, range and cross range translation. A (city-block) weighted voting method is used to reduce the impact of the more common small relative distances. To accommodate some uncertainty in the scattering center locations, the eight-neighbors of the nominal range and cross-range relative location are also probed and the translation results are accumulated for a 3x3 neighborhood in the translation space. The process is repeated with different scattering centers as reference points, providing multiple "looks" at the model database to handle spurious scatterers that arise due to articularation, occlusion or configuration differences.

To handle identification with 'unknown' objects, we introduce a criteria for the quality of the recognition result (e.g. the votes for the potential winning object exceed some threshold, $\eta_{\text{threshold}}$). By varying the decision rule parameter (typically from 1000 to 4000 votes in 50 vote increments) we obtain a form of Receiver Operating Characteristic (ROC) curve with probability of correct identification (PICI) vs. probability of false alarm (PPA).

Table 4: Example MSTAR articulated object confusion matrix (38 scatterers, ±9% amplitude tolerance, 2000 vote threshold).

<table>
<thead>
<tr>
<th>MSTAR (Public)</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>articularated objects</td>
<td>results</td>
</tr>
<tr>
<td>T22</td>
<td>ZSU</td>
</tr>
<tr>
<td>742</td>
<td>316° turret</td>
</tr>
<tr>
<td>ZSU</td>
<td>316° turret</td>
</tr>
<tr>
<td>BRDM2 (confuser)</td>
<td>32</td>
</tr>
</tbody>
</table>

Figure 11: Receiver Operating Characteristics for recognizing MSTAR articulation.

5 Recognition Results

5.1 Articulated Object Results

Table 4 shows recognition results for articulated versions of the T22 #40 and ZSU32/4 #608 at 30° depression angle, using the non-articulated versions of these same serial number objects as the models and BRDM2 #471 as an "unknown" confuser vehicle. These results, 0.990 PCl at 0.126 PPA, are obtained using a 2100 vote decision criterion with 38 scatterers and with a ±9 percent amplitude change limit. (The overall forced recognition rate is 100% over a range from 14 to 40 scattering centers.) For the conditions in Table 4, varying the vote threshold results in the ROC curve shown in Figure 11.

5.2 Configuration Variant Results

Table 5 shows a typical forced recognition confusion matrix for configuration variants in the MSTAR data at 15° depression angle, using a single configuration as the model (BMP2 #21 and T22 #133) and testing with two other variants of each vehicle type. Although more extensive T22 configuration variant data is available, only two configurations are used so that
Table 5: Forced recognition confusion matrix for MSTAR configuration variants (36 scatterers, ±9% amplitude tolerance).

<table>
<thead>
<tr>
<th>MSTAR (Public) test targets</th>
<th>Identification results [configurations modeled]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMP2 #6663</td>
<td>BMP2 [172] T72 [132]</td>
</tr>
<tr>
<td>T72 #612</td>
<td>106 (98.1%)</td>
</tr>
<tr>
<td>T72 #587</td>
<td>107 (97.2%)</td>
</tr>
</tbody>
</table>

the amount of test data for the T72 and BMP2 is comparable and the results are not artificially biased toward recognizing the T72. The optimum forced recognition result is an overall rate of 94.7%, obtained at 36 scattering centers with a translation limit of ±5 pixels and a percent magnitude change of less than ±9 percent. (The 94.7% rate for this 6D recognition engine is directly comparable to the 64.4% rate for the prior 2D version of the recognition engine given in [1].) The effect of PCI of the number of scattering centers used is shown in Figure 12 (for $l_3 = 9$) and Figure 13 shows the effect of varying the amplitude change limit (for 36 scattering centers). Using the BTR70 #c71 as an "unknown" confuser, for the optimum conditions given above, results in the ROC curve shown in Figure 14. The effect of scatterer location and magnitude invariance on the forced recognition rate for configuration differences of the T72 and BMP2 is shown in Figure 15, based on the 22 failures in 415 tests shown in Table 5. (The two cases of perfect recognition below 30% are each a single instance with no failure.) These results with actual SAR data for the 6D recognition engine show over 90% recognition for location and magnitude invariance (within one pixel and an amplitude change tolerance of 9%) values down to 41.7%, compared to the prior results [1] for the 2D engine with simulated SAR data where the recognition rate drops sharply below 40% invariance for an exact match of locations.

5.3 Depression Angle Change Results

Table 6 shows the confusion matrix for recognizing T72 #132 and BMP2 #21 at a 17° depression angle using models with the same serial numbers at a 15° depression angle and using BTR70 #c71 as an "unknown" confuser. These results, 0.855 PCI at 0.129 PFA, obtained using a threshold of 2100 votes with 34 scatterers and with an amplitude change limit of ±7%. (The forced recognition rate is greater than

Figure 12: Effect of number of scattering centers used on recognition of MSTAR configuration differences.

Figure 13: Effect of amplitude change tolerance on recognition of MSTAR configuration differences.

Figure 14: Receiver Operating Characteristics for recognizing MSTAR depression angle changes.

90% over a range of from 13 to at least 40 scatterers with the best forced recognition, 99.6%, at 34 scatterers with a ±7% amplitude change limit.) The ROC curve for these depression angle changes is shown as Figure 16.

6 Conclusions and Future Work

A significant percentage (56.5 - 61.4%) of the SAR scattering center locations are quasi-invariant (within a ±3 pixel tolerance) for object articulation, configuration differences and small depression angle changes. The magnitudes of these quasi-invariant scatterers (expressed as a radar cross section) typically change by less than ±10%. The positions and magnitudes of pairs of these quasi-invariant scatterers are used in a 6D recognition engine to achieve good recognition results with real SAR data for object articulation, configuration differences and small depression angle changes. While these three problems are similar, the differences among configurations of an object type are a more significant challenge for recognition than articulation and depression angle changes, where the model and test data are the same physical object under different conditions (as seen by comparing the ROC curves in Figure 14 with Figures 11 and 16). These recognition results are a substantial improvement over the performance of the earlier 2D recognition approach with real SAR data. Future work to incorporate additional features in the recognition engine should lead to further performance improvements and accommodate combined cases such as configuration variants along with depression angle changes.

References


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