Development and Assessment of a complete ATR algorithm based on ISAR Euler Imagery

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Outline

I. Introduction to polarimetry and the Euler parameters
II. Implementation of the full ATR algorithm
III. Testing the ATR algorithm
IV. ATR performance results
V. Conclusions
Polarimetry and Imaging

Polarimetric Scattering Matrix:

\[
\begin{bmatrix}
E^r_H \\
E^r_V
\end{bmatrix} = \left( \frac{e^{-ikR}}{2\sqrt{\pi R}} \right) \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} \begin{bmatrix}
E^t_H \\
E^t_V
\end{bmatrix}
\]

ISAR Image Formation:

[Diagram showing the process of ISAR image formation with Fourier transforms and crossrange/downrange images]
Traditional ISAR Images

T-72 Tank
Euler Decomposition

**PURPOSE:** Decompose scattering matrix into more phenomenological params

**METHOD:** Transform scattering matrix to the optimal polarization basis

Diagonalize $S$ using unitary transformation: $S_D = U^T S U$

Unitary Matrix: $U = \begin{bmatrix} \cos(\tau) & i\sin(\tau) \\ i\sin(\tau) & \cos(\tau) \end{bmatrix} \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix}$

Diagonalized Sinclair Matrix: $S_D = \begin{bmatrix} e^{i\gamma} & 0 \\ 0 & e^{-i\gamma} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \tan(\gamma) \end{bmatrix} m \begin{bmatrix} 1 & 0 \\ 0 & \tan(\gamma) \end{bmatrix} \begin{bmatrix} e^{i\gamma} & 0 \\ 0 & e^{-i\gamma} \end{bmatrix}$

Invert these equations, which is best done in power matrix form
# Euler Parameters

<table>
<thead>
<tr>
<th></th>
<th>Polarizing</th>
<th>Nonpolarizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>0°</td>
<td>45°</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Horizontal</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>Symmetric</td>
<td>Nonsymmetric</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Odd Bounce</td>
<td>Even Bounce</td>
</tr>
</tbody>
</table>

$m$ (max reflectivity)
Euler ISAR Images

Slicy

ψ  orientation (deg)

τ  symmetry (deg)

$m$  max magnitude (dBsm)

γ  bounce angle (deg)

γ  polarizability (deg)
Implementation of the ATR Algorithm

1. Find approximate center of target
2. Form image with exact back-rotation
3. Euler transform
4. Apply thresholds
5. Find possible target azimuths
6. Load library image for all targets, specific azimuth
7. Compare images
   - Register images
   - Persistence weight images
   - Compute images' average percent difference
8. Best match is lowest APD
Implementation of the ATR algorithm

Library Creation: Each vehicle of interest is measured in a compact range and back-rotated Euler ISAR images are formed for every azimuth to within 1°

Find Azimuth of Unknown Target: Extract rectangular outline of vehicle from temporary ISAR image; do simple protestation of outline until its x-axis-projected profile is narrowest
Image Formation and Exact Back-Rotation

- Fourier transforms are used to Form the ISAR Image

- Image is backrotated to 0° azimuth to simplify comparisons and allow persistence optimization

- Exact Back-rotation is used where rotation occurs as part of image formation using shifted Fourier transforms (slower but more accurate than FFTs followed by simple rotations)

\[
h(x', y') = \sum_{\phi=0}^{\phi_{\text{max}}} \sum_{f=0}^{f_{\text{max}}} H(\phi, f) e^{-i 2\pi f (x \sin \theta + y \cos \theta)} e^{-i 2\pi \phi (x \cos \theta - y \sin \theta)} df \, d\phi
\]

- Transform back-rotated ISAR images to Euler ISAR images, threshold out noise
Image Comparison

• Compare the image of the unknown vehicle to every library vehicle at the identified azimuth.

• Register the two images to be compared using the autocorrelation function.

• Calculate the percent difference between corresponding pixels and average over the whole image to obtain the APD as the correlation score.

• If persistence optimization is turned on, apply persistence weights while averaging percent difference scores.

• Identify the lowest APD score as the best matching reference vehicle and assign the unknown target this identification.
Persistence Optimization

• As part of the library creation, the azimuthal persistence of each pixel scatterer is measured

• Reliability weights are assigned so that the more persistent scatterers receive higher weights

• The weights are applied to pixel correlation scores when averaged into a weighted APD score
Testing the ATR algorithm

• A test suite of high-fidelity T-72 type tanks was chosen that differ only on the level of equipment in order to form a difficult ATR challenge

• High-quality scaled models were used. The tank geometry, material properties, and radar system were scaled properly to ensure identical results as for full-scale measurements.

• Each tank was measured at hundreds of angles in compact ranges

• The ATR performance results were formed into probability density curves and then ROC curves
The ROC Curve Definition

- Many comparison scores are formed into probability density curves.
- A decision threshold is scanned across all possible positions.
- At each possible threshold, the percent of all comparisons below the threshold that are true-positive (TP) and false-positive (FP) identifications is computed and plotted as a point on the ROC curve.
- A ROC curve closer to the top-left corner indicates better ATR performance.

![Diagram of ROC Curve and APD probability density curves](https://via.placeholder.com/150)
ATR Performance Results - Unoptimized
ATR Results – Unoptimized (zoomed)
ATR Results – Effect of Persistence Optimization

Typical of all Euler angular parameters

Typical of all magnitude parameters
ATR Score Consolidations

- The angular parameters perform too poorly even when optimized to be useful when treated separately.

- When consolidated, the Euler parameters can still improve ATR performance because they specify independent properties of the same scattering object.

- The consolidated score is defined as the distance in 5-dimensional Euler space between the Euler scores $s_i$ and some reference point $s_{i0}$.

\[ S = \sqrt{(s_m - s_{m0})^2 + (s_\gamma - s_{\gamma0})^2 + (s_\tau - s_{\tau0})^2 + (s_\psi - s_{\psi0})^2 + (s_\nu - s_{\nu0})^2} \]

- The reference point $s_{i0}$ is found by using a training data set separate from the test data sets, and adjusting the reference point for peak ATR performance.
Conclusions

• A successful, complete ATR algorithm has been developed using novel azimuth-finding, back-rotation, and persistence optimization methods.

• Using Euler ISAR images when correlation scores are persistence optimized and consolidated leads to better target recognition than traditional parameter approaches.