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AN EVOLUTIONARY APPROACH FOR 3D SUPERRESOLUTION IMAGERY

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ABSTRACT

The paper presents an evolutionary approach for 3D superresolution (SR) imagery combining the CLEAN method and an optimization procedure based on genetic algorithms (GA). Actually, this is an extension of some previously published research works on evolutionary programming (EP) based CLEAN method in 1D and 2D cases. Measured data results obtained using GA-based CLEAN-1D and CLEAN-2D are first provided in the paper. A gap is thus filled since previous works use only synthetic generated ISAR data. For the 3D case, the main idea is still to consider the reconstruction process as an optimization problem related to the residual energy of the acquired data after each scattering center (SC) extraction and cancellation. However, a new spatial dimension is added. The proposed solution takes advantage of some powerful convergence properties of GA and provides good performance in terms of both accuracy and robustness.

1. INTRODUCTION

ISAR imagery is an intermediate step in most Automatic Target Recognition (ATR) systems. Generally, 1D (range profiles) and 2D (actually, ISAR images) radar signatures are used. On-going research works are also currently performed on the 3D ISAR imagery [1]. Despite some robustness and algorithm stability issues, this extension to the 3D case is motivated by the additional information content.

Classical methods for ISAR images reconstruction are generally based on the Fourier transform [2]. SR techniques allow to overcome its drawbacks (high level secondary lobes and limited resolution) and to obtain a lower-order description of target signatures (better suited for ATR purposes). Basically, these methods are aimed to extract a scattering center (SC) description model of the target body. MEMP method [3], MUSIC [4], ESPRIT [5], linear prediction algorithms [6] and CLEAN method [7] are only several examples. The last one is an iterative technique which estimates the positions and the amplitudes of the radar target scattering centers by successive identification and cancellation of each of them in the ISAR image. Previously hidden scattering centers because of low spectral or dynamic resolution can be thus resolved. Unlike many other SR algorithms, which require LS model-based amplitude estimation, CLEAN is not a pseudospectral method. Hence, the estimated amplitudes of the scattering centers have physical meaning in this case and may be used for ATR.

The use of this method in combination with 3D radar imagery techniques enhances the quality of the extracted information about the target, which is a strong requirement for building robust ATR systems [8].

The rest of the paper is organized as follows. Section 2 provides the main idea of the proposed approach, introduces the energy function associated with the target ISAR 3D image, and describe its minimization using Genetic Algorithms. Section 3 is devoted to simulation results, while several conclusions are drawn in Section 4 together with some possible ideas for future work.

2. EVOLUTIONARY CLEAN METHOD

Iterative scattering center identification in ISAR images (2D or 3D) have to cope with numerical noise introduced by polar data formatting [4], besides the additional computation required for the imaging process itself.

In order to overcome these difficulties, an optimization formulation of CLEAN algorithm was given in [9] (1D case) and [10] (2D case). The main idea is to estimate the position and the amplitude of scattering center, so that to minimize the residual ISAR signature energy after its extraction and cancellation.

This formulation makes unnecessary the ISAR image reconstruction step and avoids the noise introduced by the polar formatting step. It is also less subject to confusions between spurious peaks and scattering centers because only a scattering center cancellation leads to a global minimum of the energy function.

However, finding this global minimum is not a simple task. Gradient Method (GM) based techniques get often trapped in a local minimum of the energy function. They successfully work only for simple forms of this function or when enough a priori information about it is known and possible to embed.

Evolutionary Algorithms (EA) are alternative, stochastic optimization methods, well suited for irregular shaped functions and where no good starting point is a priori known. EA generically denominate three approaches [11]: Genetic

Algorithms (GA), Evolutionary Programming (EP) and Evolutionary Strategies (ES).

EP based implementations of CLEAN algorithm have been already introduced in [9] and [10], for 1D and 2D cases respectively. The reported results are compared to those obtained with other SR methods, but only synthetic data are used to validate these algorithms. Some new results using measured data are presented in this paper to further validate the use of EA-based CLEAN. We propose then an extension of this work to the 3D case, which makes use of GA for the optimization procedure.

For short wavelengths, radar targets may be quite accurately modeled as a finite set of punctual, non-dispersive and isotropic scattering centers. This is the reference model in wide-band radar imagery and ATR [12]. For frequency-stepped scanning signals, the backscattered field from Q scattering centers at M sampled frequency points (f_m , $m=1,...,M$) is given by:

$$S(f_m)=\sum_{q=1}^{Q} a_q \exp\left(j4\pi f_m d_q / c\right) \tag{1}$$

where a_q is the amplitude and d_q is the distance with respect to radar system of the q^{th} scattering center and c is the speed of light.

Depending on radar capabilities and imagery methods, one could aim reconstructing 1D, 2D or 3D target ISAR images. Corresponding dimensional target signature must be acquired. In the 3D case the distance d_q is given by [13]:

$$d_q(\theta_n,\varepsilon_p)=x_q\cos\theta_n\cos\varepsilon_p+y_q\sin\theta_n\cos\varepsilon_p+ \\ +z_q\sin\varepsilon_p \tag{2}$$

where (x_q, y_q, z_q) is the Cartesian coordinate vector of the q^{th} scattering center relative to the target rotating center (having null phase) and θ_n ($n=1,...,N$) and ε_p ($p=1,...,P$) are the horizontal and vertical target aspect angles.

Most radar imagery methods require interpolating complex signature in (1) over an uniform grid in Cartesian spatial frequency space:

$$S'(f_m^x, f_n^y, f_p^z)= \\ =\sum_{q=1}^{Q} a_q \exp\left(j4\pi\left(f_m^x x_q + f_n^y y_q + f_p^z z_q\right)/c\right) \tag{3}$$

where $f^x = f\cos\theta\cos\varepsilon$, $f^y = f\sin\theta\cos\varepsilon$ and $f^z = f\sin\varepsilon$ are spatial frequencies.

However, this polar data formatting step introduces interpolation numerical noise. This is unavoidable in most of radar imagery techniques and also in classical CLEAN, which searches maxima in the reconstructed ISAR image. Hence, it is very interesting to use a different approach, based on Eq. (1) rather on Eq. (3). This way, polar data formatting is avoided.

The scattering center parameters a_q and (x_q, y_q, z_q) are not estimated anymore by locating maxima in the reconstructed ISAR image, but as solutions of the following cost function minimization problem:

$$\min E=\left\| S(f_m,\theta_n,\varepsilon_q)-a\exp\left(j4\pi f_m d(\theta_n,\varepsilon_p)/c\right)\right\|^2 \tag{4}$$

where $d(\theta_n,\varepsilon_p)$ is given by Eq. (2), while $S(f_m,\theta_n,\varepsilon_p)$ is the target complex signature obtained by combining Eq. (1) and (2) (see also Eq. (5) and (6) in [13]).

The cost function in (4) is the residual energy of the target signature after cancelling the current scattering center using their amplitude and position estimates.

Note that this is an iterative process. After each scattering center extraction and cancellation, the procedure starts again with the new, reduced target complex signature as input. This continues until a specified number of scattering ceters is extracted or the residual energy falls under a pre-defined threshold.

The 2D version of the algorithm presented above follows directly from the equations (1) to (4), for $P=1$ and $\varepsilon_1=0$ [9]. Subsequently, $N=1$ and $\theta_1=0$ leads to the 1D case [10].

An example of energy function in the 1D case is illustrated on figure 1. The solution point issued from the minimization process is also indicated for both GM and GA. Note that unlike GM, the global minimum was successfully identified by GA.

At each iterative step, GA are used to solve optimization problem expressed by (4). GA implementation steps are given bellow:

Step 1 (Initialization). First generation of random-valued individuals is created.

Step 2 (Evaluation). Objective function is evaluated for each individual in generation, resulting in its cost.

Step 3 (Selection). Selection is performed on individuals (with variants, see below).

Step 4 (Crossover). New individuals are generated via crossover operator from selected individuals.

Step 5 (Mutation). New individuals are generated via mutation operator.

Step 6 (Evaluation). Cost (objective function) is evaluated for all individuals in global set resulted from selection, crossover and mutation.

Step 7 (Termination check). If none of termination criteria (maximum number of iterations, execution time, cost below specified level) are met, proceed to step 3.

Different variants for selection operator (step 3) may be used. Widely spread is selecting best fitted individuals (sometimes with a degree of randomness). Usually, the best-fitted individual enjoys special status: either it is “immortal” (its selection is guaranteed), either it is stored and reinserted periodically among current generation individuals.

When algorithms exits (meeting one or more termination criteria), provided values for *a* and (*x, y, z*) are assigned to the extracted scattering center. Then its ISAR complex signature is computed and subtracted and algorithm continues with the resulting reduced ISAR signature as input.

Numerical values of GA generation size and of crossover and mutation rate may vary. We used relatively small generation size ($40\div 50$ individuals), crossover rate of 0.4 and a mutation rate of 0.04 . GA terminated when either 2000 iterations were reached or if for 200 successive

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iterations no significant gain in cost has been recorded. Selection operator used a fitness criterion with weighting random component. The best-fitted individual has been reinserted each 20 iterations in GA population.

Since no straightforward method to choose GA parameters exist, 10 uniformly spaced values of crossover rate have been tried, from 0.1 to 0.9 . Mutation rate has been chosen 10 times smaller than the crossover rate. The best trade-off between the cost function minimization and the convergence speed has been found to lie around 0.4 .

The computing time may largely vary between different simulations, but generally the computational burden associated to the GA remains important. In most cases simulations required more than 30 minutes to converge (on a 1.4 GHz P4 processor), while the mean time required for extracting 9 scattering centers was 6 h.

The choice of a relative small size of population has been imposed by computing time constraints. However, even if larger populations should provide higher probability of convergence to global minimum, in practice we found our choice satisfactory for demonstrating purposes.

3. SIMULATION RESULTS

Both synthetic and real data has been used to evaluate the GA based CLEAN method in the 2D case. The real data was acquired by measuring a scale reduced model of a DC-3 plane in the anechoic chamber of ENSIETA (see figure 2).

Figures 3 and 4 present the results provided by the scattering center extraction procedure using GA-based CLEAN for a synthetic target. Note that in the 2D case, the two central scattering centers are not resolved in the Fourier image. CLEAN method identifies them, but they are (slightly) shifted. A false scattering center is also detected due to the resolution limitation.

The method has been also tested on real data. ISAR image (or range profile) has been reconstructed with both GA-based CLEAN and MUSIC methods.

In the mono-dimensional case, the results are depicted on figure 5. 8 scattering centers have been extracted with GA-based CLEAN, while MUSIC algorithm identifies only 4 strong scattering centers and 2 other ones much weaker (see around -0.4 and 0.8 in slant range). Amplitudes estimated with CLEAN method have a physical meaning, increasing the information content about the target.

Figure 6 illustrates the way in which CLEAN operates. While the left peak could easily be misinterpreted as a singular echo, it is resolved by CLEAN in three separate scattering centers, two of them appearing only after successful removal of the dominant echo.

In a similar manner, but for the 2D case, the results are depicted on figure 7 (comparison of CLEAN extracted scattering centers using Fourier and MUSIC reconstructed ISAR images). Once again, unlike MUSIC method, CLEAN also provides consistent amplitude information. Finally, figure 8 shows a scattering center extraction sample using CLEAN-2D algorithm.

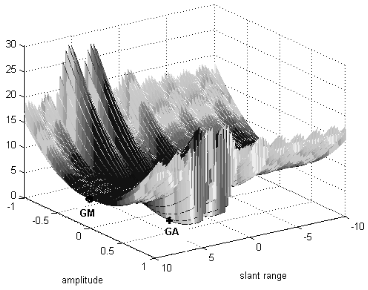

Figure 1 – Energy function example (1D case) and minimization with Gradient Method (GM) and Genetic Algorithms (GA)

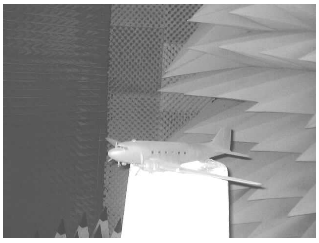

Figure 2 – DC-3 model in the anechoic chamber

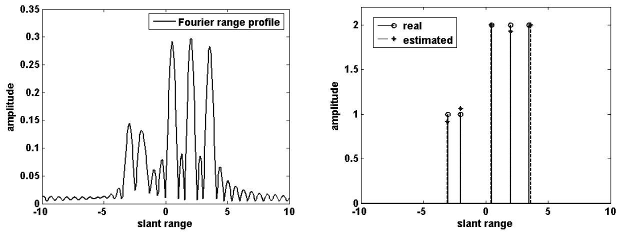

Figure 3 – Fourier range profile (left) and CLEAN 1D extracted SC (right) for the synthetic target

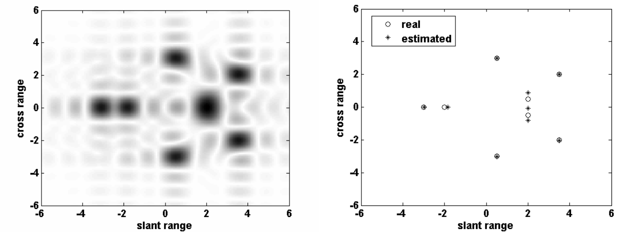

Figure 4 – Fourier ISAR image (left) and CLEAN 1D extracted SC (right) for the synthetic target

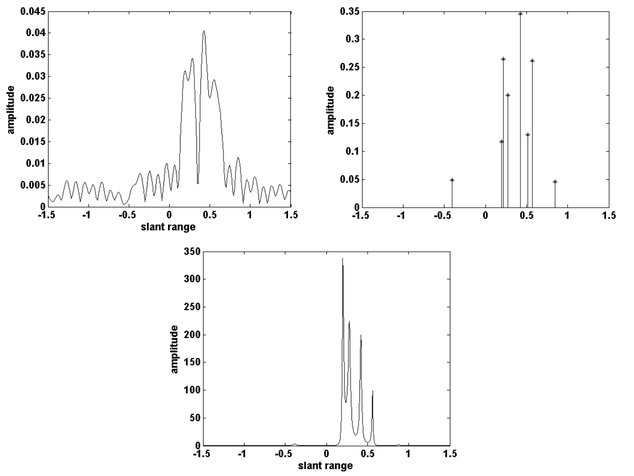

Figure 5 – Fourier range profile (top left), MUSIC range profile (top right) and SC extracted with CLEAN (bottom) for the DC-3 target

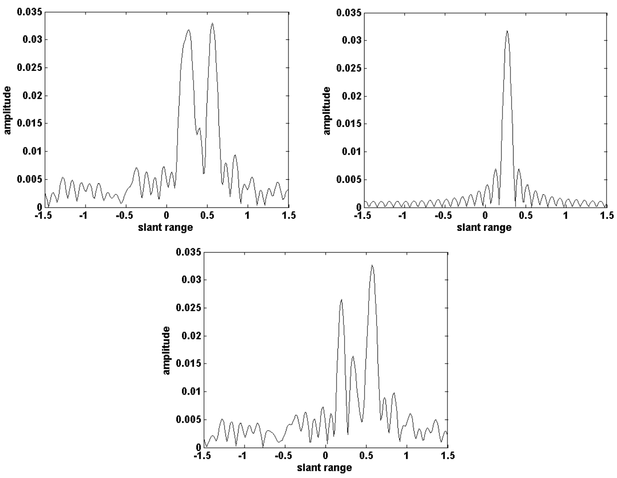

Figure 6 – SC extraction for the DC-3 target using CLEAN 1D

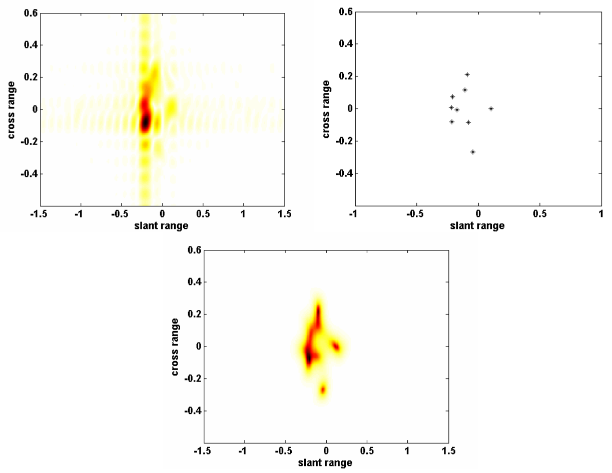

Figure 7 – Fourier ISAR image (left), MUSIC ISAR image (right) and SC extracted with CLEAN (center) for the DC-3 target

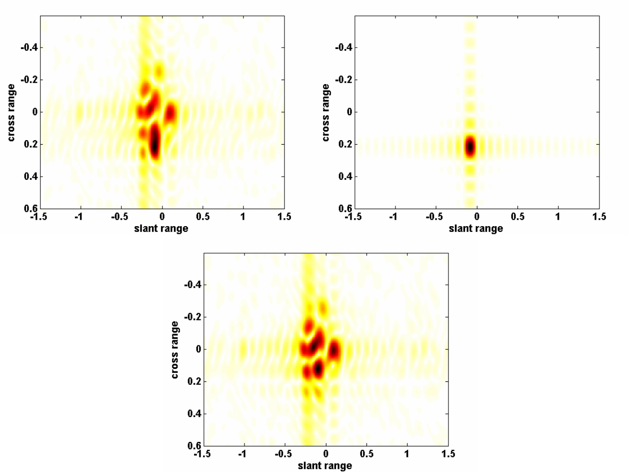

Figure 8 – SC extraction for the DC-3 target using CLEAN-2D

For the 3D case, synthetic signatures have been simulated in the X band, using data given in table 1. A frequency-stepped signal centered on 10 GHz has been used, with a frequency step of 7.5 MHz. The combination of these parameters results in a 3D 20x20x20 m ambiguity window.

The scattering center model extracted using GA-based CLEAN 3D is shown on figure 9. Position estimation is accurate for most extracted scattering centers. Only two of them are slightly shifted. Non distinguishable in Fourier-reconstructed ISAR image because of low resolution, central scattering centers become visible during iterative CLEAN algorithm.

In the second simulation we have added white Gaussian noise to the previously used ISAR signature.

For each scattering center of amplitude a, a Gaussian noise map of variance σ^2 is generated, using the following definition of the signal-to-noise ratio:

$$SNR = 20\log\left(a/\sigma\right) \tag{5}$$

The noisy ISAR signature is then obtained by superposing all the noise maps to the synthetic signature [4].

In a similar way, the scattering center model extracted using GA-based CLEAN 3D is shown on figure 11, while figure 12 presents an example of scattering center extraction in noisy case. Again, scattering center positions are retrieved with good approximation.

Numerical values (truncated to the most 2 significant digits) for Cartesian coordinates and amplitudes of the scattering centers extracted in noise-free and SNR=10dB cases are given in table 2. Note that the two central scattering centers (#5 and #6), unresolved in the Fourier image are recovered by the CLEAN algorithm in both cases (figures 10 and 12). The price to pay is some accuracy loss in amplitude estimation, a slight position shifting for the two scattering centers and the detection of an artifact scattering center (#0).

Note that an amplitude map, accounting for anisotropy and geometrical masking can be associated to each extracted SC, to obtain a better model matching [14].

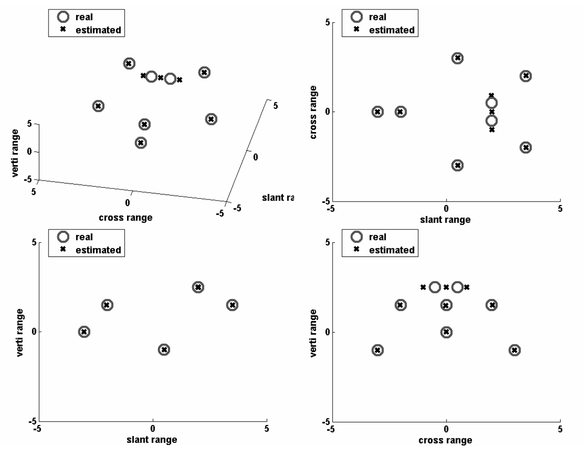

Figure 9 – Original and estimated positions for the 3D synthetic target (noise-free)

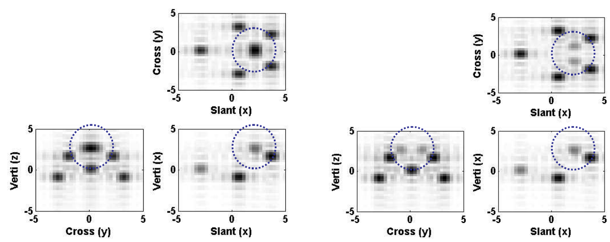

Figure 10 – Example of CLEAN estimated SC cancellation (left: before; right: after) for the 3D synthetic target (noise-free)

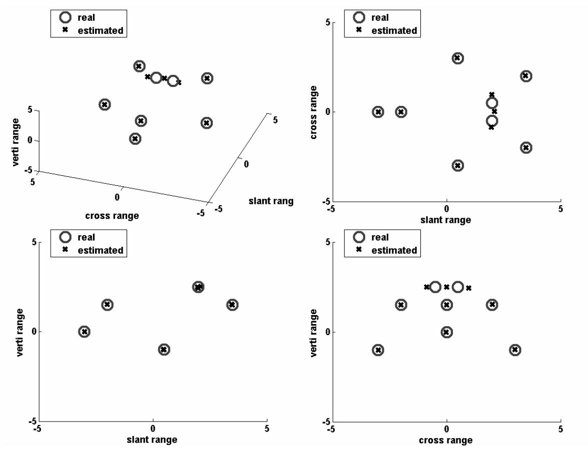

Figure 11 – Original and estimated positions for the 3D synthetic target (SNR=0dB)

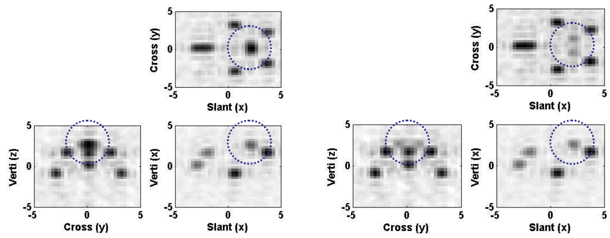

Figure 12 – Example of CLEAN estimated SC cancellation (left: before; right: after) for the 3D synthetic target (SNR=0dB)

Table 1 – Synthetic target SC positions and amplitudes

#	x	y	z	a
1	-3	0	0	1
2	-2	0	1.5	1
3	0.5	-3	-1	1
4	0.5	3	-1	1
5	2	-0.5	2.5	1
6	2	0.5	2.5	1
7	3.5	-2	1.5	1
8	3.5	2	1.5	1

Table 2 – CLEAN estimated SC positions and amplitudes

	Noise-free				SNR=10dB			
#	x	y	z	a	x	y	z	a
0	2.01	0.00	2.50	1.17	2.11	0.02	2.51	1.19
1	-3.00	0.00	0.00	0.99	-2.98	-0.00	-0.00	0.98
2	-2.01	-0.00	1.48	0.99	-1.98	0.00	1.51	0.96
3	0.50	-3.00	-0.99	0.99	0.49	-2.99	-0.99	0.97
4	0.50	3.00	-0.99	1.05	0.47	3.01	-0.99	1.05
5	2.00	-1.00	2.48	0.48	1.97	-0.86	2.49	0.43
6	2.00	0.90	2.50	0.45	2.00	0.97	2.43	0.42
7	3.50	-2.00	1.50	0.98	3.49	-1.99	1.50	0.95
8	3.50	2.02	1.50	1.06	3.46	2.01	1.52	1.08

4. CONCLUSIONS

GA-based CLEAN method is an effective tool for extracting the positions and amplitudes of the scattering centers. GA successfully meets the optimization challenge associated to the CLEAN algorithm in the 3D case, confirming previous results for 1D and 2D ISAR signatures.

Evolutionary CLEAN also allow estimating the amplitudes of the recovered scattering centers. Furthermore, it avoids numerical noise introduced by data polar formatting step and demonstrates accuracy, SR behavior and robustness.

Future work will include extensive noise robustness tests and 3D measured ISAR data processing. We also plan to compare the proposed method to other techniques, such as RELAX algorithm [15] for example.

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