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Pattern synthesis of MIMO radar based on chaotic differential evolution algorithm

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ABSTRACT

A Chaotic Differential Evolution (CDE) Algorithm based method for pattern synthesis of MIMO radar is proposed. By optimizing positions and excitation amplitude of the element in receive and transmit array, better control of side lobe level and null depth can be achieved. CDE which is proposed by introducing Chaotic Optimization (CO) mechanism to Differential Evolution (DE), the risk of getting local optimal position can be reduced, thus the premature of DE can be avoid, and the performance of global optimization is improved. Simulation results validate the effectiveness of the proposed method and superiorities.

1. Introduction

MIMO radar is considered to have many advantages, such as the ability of strong parameter identification [1], high spatial resolution [2], fluctuation of target detection performance [3], and the ability to avoid Radar Cross Section (RCS), and so on, thus more and more researchers and scholars give more attentions to MIMO radar.

The basic Exhaustive Search (ES) algorithm disturbed the vector by the probability distribution of the problem, and enumerates all the possible results which according to some rules then inspect the results step by step, until optimal solution that meets demand is found or all the enumeration has been inspected, so more manual participation is needed thus made ES more complex. However, with the shortness of "after- effect", the method of Dynamic Programming [4,5] can only get the local optimal result. Random methods with generality and ability of global optimization are gradually applied to array synthesis from the 90s, such as Genetic Algorithm (GA) [6,7], Particle Swarm Optimization (PSO) [8,9] . In literature [10] GA was used to optimize MIMO radar arrays, and the side lobe is lowered in the two-way pattern, but by the limit of local optimization ability, the optimal level is limited. To reduce the risk in "premature" convergence of GA, literature [11] proposed Improved Adaptive Genetic Algorithm (IAGA), with the fitness of the population and convergence generation, the parameters of crossover and mutation adaptively change themselves to increase the possibility of getting global optima solution. CO is a regular, ergodic and sensitive search algorithm [12,13], which search the results by both the positive and negative direction. In literature [14], Joseph O. et al. used Rossler CO to model, simulate and analyze the beaming forming problem of MIMO radar, better results in Doppler frequency shift and angular resolution are generate, at the same time obvious main lobe can be produced. In literature [13], Fuxin et al. used a mixed algorithm based on GA and CO, taking advantage of the regular searching of CO, the premature of GA can be avoid, and capability of global search is enhanced, and then applied to optimize t-MIMO radar, lower side lobe level can be obtained.

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In MIMO radar application environments, which the influence of natural environment on the reflection and refraction of electromagnetic waves, especially effects on radar waves in the ionosphere, makes radar signals led to some decline in varying degrees. At the same time human disturbances, such as construction work, human-generated electromagnetic signal around the flying target may have serious interferences on the radar signals. The interference may cause serious distortion of signals and, ultimately, on target detection results. However using stochastic optimization algorithm for MIMO radar research process is typically used in a probabilistic manner to make optimal results out of the local optimal solutions, but which is not conducive to improving efficiency. Stochastic optimization algorithm in optimal value of reservations did not make full use of effective population information in the process, which is not conducive to the optimal solution [15]. Based on the above issues paper CO in mechanism into the DE algorithm, chaos differential evolution algorithm (Chaotic Differential Evolution, CDE) algorithm and researching in MIMO radar array, zero depth and application of side lobe level of optimization.

2. MIMO radar model

Assuming that the number of the transmit and receive array are N_T and N_R, and the minimum spacing between two array elements is d, and the carrier wave length λ and the target length D satisfy the MIMO radar relevant criteria $d > \lambda R/D$. In order to make sure that the signal from each array element won't have interference with each other, the minimum array spacing must not less than $\lambda/2$.

MIMO radar uses Omni-directional antennas for each array, but the actual radar requires strong directionality, we known that the direction function of MIMO radar antenna array is the product of the direction function of each antenna and the function of the array direction from the antenna pattern product principle, then MIMO array directionality needs to be stronger, namely each array required to bear ranged by a certain way and excitation amplitude of each array need to meet the relevant criteria. By the array antenna theory, the direction functions of MIMO radar transmitting sub-array and receiving sub-array respectively are

$$f_T(u) = |\sum_{i=0}^{N_T-1} A_{Ti} \exp(j\frac{2\pi}{\lambda}\alpha_{Ti}u)| \tag{1}$$

$$f_T(u) = |\sum_{k=0}^{N_R-1} A_{Rk} \exp(j\frac{2\pi}{\lambda}\alpha_{Rk}u)| \tag{2}$$

where α_{Ti} and α_{Rk} represent the location of the i-th parameter in the transmitting array and k-th parameter in the receiving array, respectively, A_{Ti} and A_{Rk} are the excitation amplitude that corresponds to α_{Ti} and α_{Rk}. $\mu = \sin\phi - \sin\phi_0$, ϕ and ϕ_0 are the pointing angle and antenna beam direction of the plane wave and the array normal. For any ϕ, $\phi_0 \in [-\pi, \pi]$, we will have the limit ϕ, $\phi_0 \in [-\pi, \pi]$. The main lobe of the pattern is located at $u = 0$, and the pattern of the antenna is symmetric about u, thus means that $p(u) = p(-u)$, it's also symmetric about $u = -1$, so $p(1 + \Delta u) = p(1 - \Delta u)$, this showed that just the scope in $0 \le u \le 1$ needs study.

As the orthogonal signal is used in MIMO radar antenna, the transmitting ends use orthogonal waveform, the received signal will be flitted by matching filter at the receiving end, then digital wave is got after the signal is processed by beam formers. By the principle of MIMO radar, the pattern of the MIMO radar could be expressed as

$$f_{MIMO}(u) = |\sum_{i=0}^{N_T-1} A_{Ti} \exp(j\frac{2\pi}{\lambda}\alpha_{Ti}u) \cdot \sum_{k=0}^{N_R-1} A_{Rk} \exp(j\frac{2\pi}{\lambda}\alpha_{Rk}u)| = |\sum_{i=0}^{N_T-1}\sum_{k=0}^{N_R-1} A_{Ti}A_{Rk} \exp(j\frac{2\pi}{\lambda}(\alpha_{Ti} + \alpha_{Rk})u)| \tag{3}$$

The last equation equal the Kronecker product of the pattern functions of the transmitting arrays and that of the receiving arrays

$$f_{MIMO}(u) = |\sum_{k=0}^{N_R-1} \exp(j\frac{2\pi}{\lambda}\alpha_{Rk}u)| \otimes |\sum_{i=0}^{N_T-1} \exp(j\frac{2\pi}{\lambda}\alpha_{Ti}u)| = f_T(u) \otimes f_R(u) \tag{4}$$

In fact that the computation is much less when use Eq. (3) than Eq. (4).

3. MIMO radar pattern synthesis by CDE

3.1. Chaotic differential evolutionary algorithm (CDE)

DE [17] was firstly introduced in the International Evolutionary Computation Competition in 1996, the results showed that DE was one of the fastest methods. R. Storn et al. presented the detail progress in Journal of Global Optimization, which is the start of DE's time.

When DE is applied to solve problem, the difference between the population would get smaller late of the convergence progress because of the crossover and mutation operate, therefore DE has the risk of "premature". Chaotic Optimization has the feature of ergodicity and randomness and so on [18,19], so the mechanism of CO is introduced into DE algorithm, and the population would be optimized the mechanism of CO further, which would led the population getting away from the local optimal position, thus the population was disturbed, so the global optimization ability of DE is promoted, and avoid the shortness of DE.

The basic realization of DE algorithm is

(1) assume that the initial population meets the limit $\left\{x_i(0)|x_{j,i}(0) \in [x_{j,i}^L, x_{j,i}^U]\right\}$, ($i$ = 1, 2, ..., NP, j = 1, 2, ..., D), that NP is the number of the chromosome (namely the size of the population), D is the number of the genes (namely the dimension of a particle), the initial population is generated as the following

$$x_{j,i}(0) = x_{j,i}^L + rand(0,1)(x_{j,i}^U - x_{j,i}^L) \tag{5}$$

in which, $rand(0, 1)$ is a random number between 0 and 1.

(2) mutation.

The new population is generated as the following

$$v_i(g+1) = x_{r1}(g) + F[x_{r2}(g) - x_{r3}(g)] \tag{6}$$

where $r_1 \neq r_2 \neq r_3$, F is a mutation factor, $x_{r1}(g)$ is one of the g-th generation population. What's more, each of the population should be under the limit as that in (1).

(3) crossover.

If j_{rand} is a random integer between 1 and D, so the g-th generation population and the temporary population do crossover as the follows

$$u_{j,i}(g+1) = \begin{cases} v_{j,i}(g+1) & (if(rand(0,1) \leq CR) or (j = j_{rand})) \\ x_{j,i}(g) & others \end{cases} \tag{7}$$

(4) selection.

Greedy selection method for the population is used in DE algorithm,

$$x_i(g+1) = \begin{cases} u_{j,i}(g+1) & if(fit(u_i(g+1) \leq f(x_i(g)) \\ x_i(g) & others \end{cases} \tag{8}$$

where $fit(p)$ is the fitness value of p.

In literature [20] a chaotic system is proposed as

$$y_{k+1} = \kappa y_k(1 - y_k) \tag{9}$$

where κ is a control parameter, when $\kappa = 4$, $y_1 \in (0, 1)$ and $y_1 \neq \{0.25, 0.5, 0.75\}$, Eq. (9) is a chaotic system.

To improve DE by introducing the mechanism of CO is that in the iteration of the algorithm, the local best was found by DE, and then population would continue to iterate k times near the local best

$$x_{k+1} = x_{best} + \psi y_k \tag{10}$$

Then the fitness of the DE population and the improved algorithm population is compared, and the population which has better fitness could be reserved and. In Eq. (10), $y_k$is calculated by Eq. (9), and the regulatory factor ψ is

$$\psi = \begin{cases} 1 & if(r \geq 0.5) \\ -1 & others \end{cases} \tag{11}$$

where r is a random number between 0 and 1, and the regulatory factor could lead the chaotic population update by two wards, thus the positive and negative wards.

By introducing CO mechanism into basic DE, the improved algorithm mast be more complexity in the aspect of time and space, but as the search mechanism continues with the local best of DE population, the optimized result is better, and the mechanism of CO can reduce the risk of DE's premature. Fig. 1 is the pseudo of the CDE and Fig. 2 compares CDE algorithm and DE in the aspect of optimization.

3.2. Pattern synthesis of MIMO radar based on CDE

When solving MIMO radar sparse array optimization, due to the discrete issues, we first encode the position of the transmitting and receiving array in the binary and randomly initialize array excitation amplitude.

Assume that the sparse ratio of MIMO radar transmitting arrays and receiving arrays are η_R and η_T, transmitting array has N_T arrays, receiving array has N_R arrays. If "1" indicates that there is array in the grid position, "0" indicates that there is no array in the grid position, then the binary encoding vectors$\boldsymbol{S}_T$ &tpcheck; $\boldsymbol{S}_R$ of the transmitting array and receiving array of MIMO radar antenna are respectively expressed as

$$\boldsymbol{S}_T = \left\{ 1 \quad \Xi_{N_T/\eta_T - 1}^{N_T - 2}(1, 0) \quad 1 \right\} \tag{12}$$

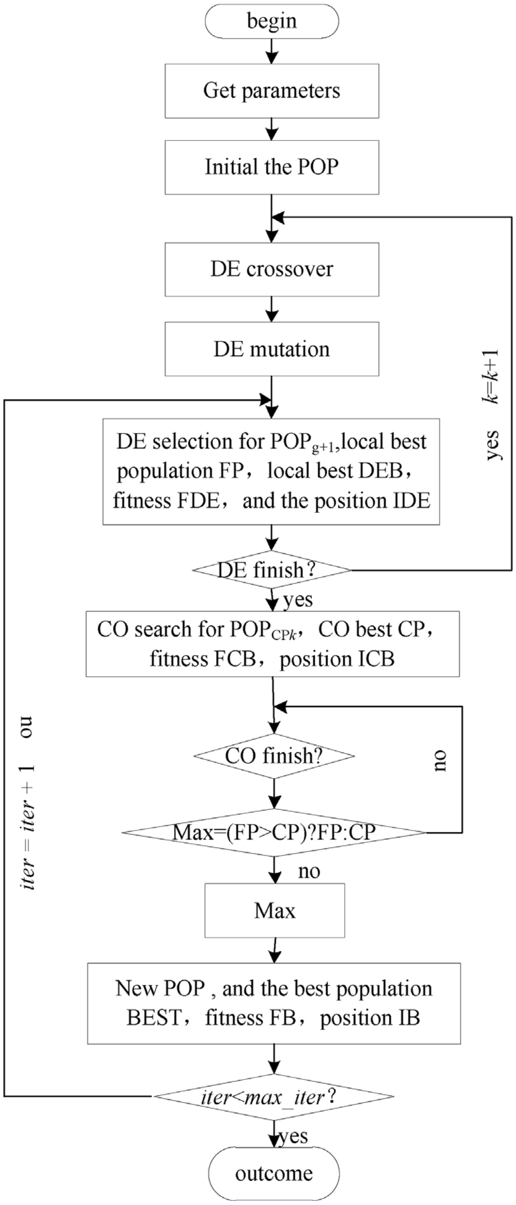

Fig. 1. Pseudo of CDE.

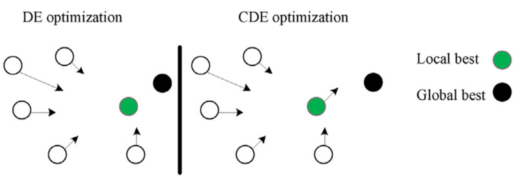

Fig. 2. The compare of DE and CDE optimization proscess.

$$\boldsymbol{S}_R = \left\{ 1 \quad \Xi_{N_R/\eta_R-1}^{N_R-2}(1,0) \quad 1 \right\} \tag{13}$$

Where $\Xi_M^N(a,b)$ expresses that N elements are in the vector having M elements, and the rest M-N elements are b.

WeobtainabinaryencodingvectorofMIMOarraycombining(5)and(6)

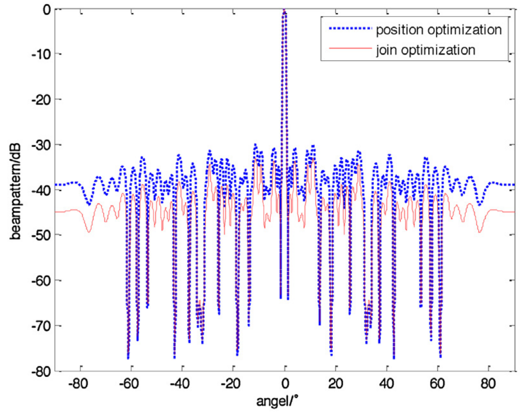

Fig. 3. Comparison of position optimization and joint optimization.

$$\boldsymbol{S}_M = \left\{ \overbrace{1 \quad \Xi^{N_T-2}_{N_T/\eta_T-1}(1,0) \quad 1}^{\boldsymbol{S}_T} \quad \overbrace{1 \quad \Xi^{N_R-2}_{NR_R/\eta_R-1}(1,0) \quad 1}^{\boldsymbol{S}_R} \right\} \tag{14}$$

Algorithm fitness function usually associated with side lobe levels of MIMO synthesis pattern. If f_{CL} represents the main lobe level, f_{SL} represents the side lobe level, then the normalized peak side lobe level is

$$PSLL = 20 \cdot lg \frac{\max(f_{SL})}{\max(f_{CL})} \tag{15}$$

Considering the null depth, then the fitness function can be expressed as

$$fn = \omega_1 |PSLL - ESLL| + \omega_2 |MNUL - ENUL| + \omega_3 |NU\_SD| \tag{16}$$

where PSLL is peak side lobe level, $ESLL$ is target peak lobe level; $MNUL$ represents average null depth, $ENUL$ represents target null depth; NU_SD represents null variance, ω_1,ω_2,ω_3 respectively represents the weighting factor of side lobe level, null level and null fluctuations.

Assume that

$$\boldsymbol{E}_M = rand(1, N_R + N_T) \tag{17}$$

is a vector, in which the parameters are all between 0 and 1, the initial excitation of the array is the dot product of $\boldsymbol{S}_M$ and $\boldsymbol{E}_M$, so the amplitude of the array is

$$\boldsymbol{A}_M = \boldsymbol{E}_M. \times \boldsymbol{S}_M \tag{18}$$

From the analysis above, the target function for MIMO radar pattern synthesis is

$$f_g = \max(fit) \tag{19}$$

4. Numeric results

Assume that $NP = 32*2(N_T = N_R = 32)$, $D = 64$, the max iteration is 500, the min spacing is $\lambda/2$. The expected peak side lobe level is $ESPL = -15.00dB$, target null level is $ENUL = -95.00dB$, $F = 0.05$, $CR = 0.7$, the simulation includes the joint optimization of arrays' position and amplitude, joint optimization of the side lobe level and null level, and the compare of several algorithm.

Simulation 1: joint optimization of arrays' position and amplitude.

The sparse parameter of the transmitting end and the receiving end is 0.34 and 0.44, and the weighting factor is $\omega_1 = 0.8$,$\omega_2 = 0.15$, $\omega_3 = 0.05$. Fig. 3 is the comparison of position optimization and the joint optimization of position and amplitude, in the 100 times optimization by CDE, the best join optimization result is $PSLL = -33.02$ dB, the mean side lobe is -33.0045 dB, and at the same time, the min null level is -76.32 dB, and Fig. 4 is the transmitting and receiving arrays' position which corresponds to Fig. 3.

Simulation 2: comparison of the optimization result of CDE and the result in literature [21]. Assume that the number of the population is $NP = 30$, $CR = 0.58$, $F = 0.35$, the max iteration is 1000, the number of transmitting array and receiving array are both 25, then the simulation is conduct, the peak side lobe is -23.16 dB by CDE proposed in this paper, which is shown in Fig. 5.

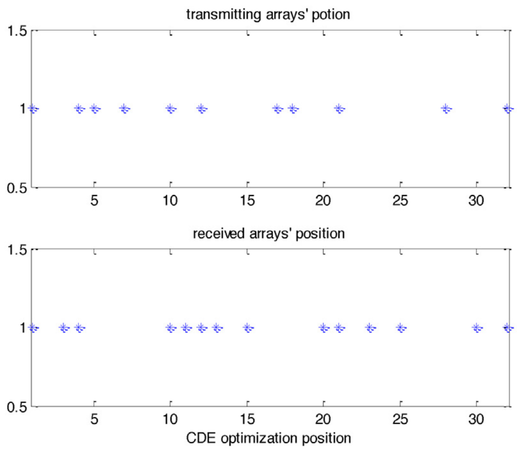

Fig. 4. MIMO arrays' position of joint optimization.

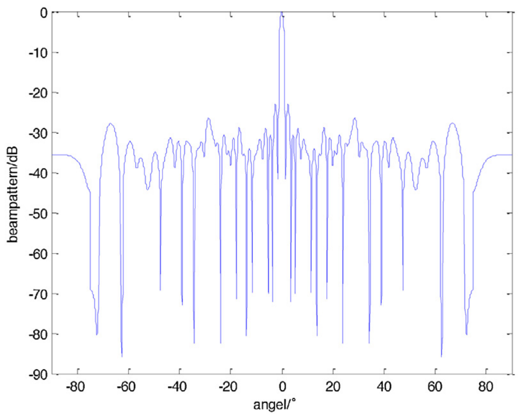

Fig. 5. Comparison of CDE and literature [21].

And the optimization by DE in literature [21] is −22.63 dB, the comparison shows that the newly proposed algorithm is better than DE, thus means CDE is more efficiency than DE.

Simulation 3: joint optimization of side lobe level and null depth level.

If the sparse factor of the transmitting arrays and the receiving arrays are 0.15 and 0.18, and the weighting factor is$\omega_1 = 0.8$,$\omega_2 = 0.2$, $\omega_3 = 0$. 1000 times simulation was conducted for the optimization of MIMO radar's pattern by CDE, in order to strengthen the anti-jamming ability of MIMO radar, −100 dB null depth should be formed at the direct of $\pm 60^\circ$, $\pm 25^\circ$and $\pm 15^\circ$. Fig. 6 is the simulation result, it shows that the depth at $\pm 60^\circ$ and $\pm 15^\circ$ meets its expectation, and at $\pm 25^\circ$ the result is better than its expectation, but if high performance computer is used in the simulation, better results would expect to increase.

Simulation 4: comparison with AGA in literature [10].

In literature [10], the number of the transmitting array and receiving array are 25, the excitation amplitude of all the arrays' element is 1, and the aperture of the arrays is50λ, and the max iteration is *miter* = 1000, the termination condition is *iter* = *miter* or the peak side lobe *PSLL* < −30 dB, the result shows in Fig. 7. In the figure, the peak side lobe is −30.93 dB, however the results is −28.65 dB by Adaptive Genetic Algorithm (AGA) in literature [10], it shows that CDE performs better than AGA in the aspect of side lobe optimization.

5. Conclusion

In this paper, Pattern Synthesis of MIMO radar by the hybrid approach CDE based on Chaotic Optimization and Differential Evolutionary Algorithm is studied. By introducing the mechanism of CO into DE, which could disturb the population of DE by CO, strengthened the ability of global optimization. The numeric results showed that CDE could be used for the joint optimization of the arrays' position and the arrays' amplitude, and the joint optimization of the side lobe level and null depth level, so the global optimization performance and the search accuracy of DE is improved. Later work could introduce

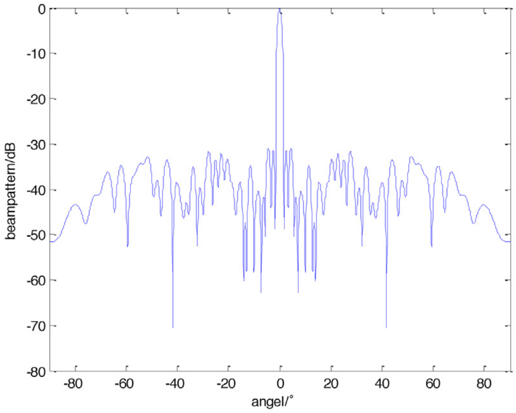

Fig. 6. Joint optimization of side lobe and null depth by CDE.

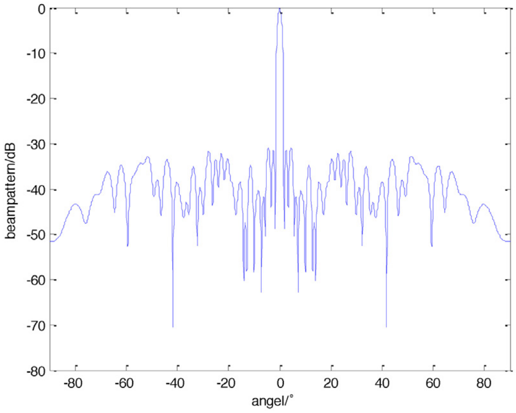

Fig. 7. Comparison of the result of CDE and AGA in literature [10].

the deterministic algorithm into random algorithm, so new method would be proposed for the optimization of MIMO for better results [22].

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