Method of Radar Power Control under Search State

Xiang Zhang\textsuperscript{a}, Hua Wu\textsuperscript{b}

Aeronautics Engineering College, Air Force Engineering University, xi’an710038, China
\textsuperscript{a}cmaristotle@163.com, \textsuperscript{b}310128135@qq.com

Abstract. To improve radar radio frequency stealth performance, a method of radar power control in search condition is proposed. Taking constraint condition of search frame period and detecting probability into consideration, target function of lowest radiation energy based on grey relational degree is set up, which combines detecting performance and radiation energy. An improved particle swarm optimization (IPSO) algorithm, which adjusts weight self-adaptively, changes learning factors asynchronously and introduces compensating particle to search the blind area, is proposed to solve the target function. The simulation shows that the proposed method can realize lower radiation energy on the premise of ensuring the detecting probability. In addition, it has better performance of radio frequency stealth.

1. Introduction

The full-open-full-close working mode of traditional Radar has been unable to meet the demand of modern electronic warfare. Unlike traditional mechanical scanning radar, the working parameters of phased array radar are dynamic and variable, its radiation power can be changed by controlling its array. With the development of passive detection system, radar will be easy to expose, be intercepted, and interfered, or even attacked by the enemy. Therefore, during the real war, the radio frequency (RF) stealth characteristics of airborne radar should be considered in power control strategy [1-2].

There are many researches on radar power control, especially control the transmission power through beam formation. Literature [3] introduced the method of controlling search energy under the condition of prior knowledge or not, and a method of radar power control under tracking state based on covariance control, information increment and target mobility characteristics is given, it has introduced the method of radar power control comprehensively. Literature [4-6] researched on the receiving beam. According to the interactive multi-model tracking algorithm and covariance control method, an adaptive sampling interval selection method for target tracking is proposed [7]. In literature [8], the realization method of the minimum power strategy and minimum resident strategy is deduced theoretically. Literature [9] proposed a real-time control method of single radiation energy in radar tracking state. In literature [10], the radar power is classified according to the target distance and RCS, and the classification criterion is confirmed. Literature [11] transformed the zero-point control of the transmitting beam into a constrained optimization problem.

Different radar States has different properties. For instance, radar should found targets quickly in a large area under search state, while stable and accurate tracking of a target in a small area under tracking state. Therefore, the radar power control method under different state should be different, and there few researches on radar power control under the search state. In this paper, according to radar
operating characteristics under search state, an objective function of radar radiation energy based on RF stealth was set up, and the spatial, temporal and energy domain constrains were built under the premise of ensuring the detection probability. Then, an improved particle swarm optimization (IPSO) was proposed, we improved the weight and learning factors, which enhance the global search ability, local improvement ability and convergence ability, and we introduction of Gaussian compensation particle to realize the search of blind spot, which enhances the diversity of particles. The simulation shows that; our radar power adaptive control method increases the detection probability while the radiation power is smaller, therefore, the RF stealth performance is enhanced.

2. Objective Function
While achieve the expected detection probability, radar should avoid waste of energy as much as possible, in another word, under the condition that radar meets certain detection probability, the radiation resources are the smallest, which is the maximum target that needs to be achieved in the search state. According to this criterion, the objective function was built as follow:

$$L = \frac{\sum_{i=1}^{N} P_i f_i N_{\text{beams}i}}{\text{grey}_\text{relation}(P_i, P_e)}.$$

Where, $N$ is the search partition number, $P_i$ is the average transmission power in area $i$, $P_e$ is the estimated detection probability vector, $P_e$ is the expected detection probability vector, grey_relation() is the grey relation function, which means proximity. Less the value is, less resources are waeted, and the RF steath ability is better.

3. Parameter Determination

3.1. Wave figures
The search priority for each partition is determined according to prior knowledge, and determine the arrangement of the beams according to different priorities. Mian arrangement including square arrangement and hexagonal arrangement. As shows in fig.1, they are suitable for areas with high threat level and low level:

![Beam arrangement](image)

(a) Square arrangement  (b) hexagonal arrangement

Figure 1. Beam arrangement.

The wave figure of the search area is determined as follow:

$$N_{\text{beams}} = \frac{1}{4} \frac{4}{\pi} \left( y^2 + \csc \left( \frac{\theta_2}{2} \cos (\theta - \alpha) \right) \cdot [\sin (\theta_2 - \alpha) - \sin (\theta_1 - \alpha) \left[ \sin (\phi) - \sin (\phi) \right] ]\right).$$

(2)
Where, \( p=1 \) represents square arrangement, and \( p=2 \) represents hexagonal arrangement, \( \varphi \) represents the half-power bandwidth of the needle plane normal direction, \( \theta_1, \theta_2 \) are the upper and lower bound of the pitching angle, \( \phi_1, \phi_2 \) are the upper and lower bound of the azimuth, \( \alpha \) is the pitching angle of the antenna array plane.

3.2. Search frame cycle

For phased array radar, the search frame cycle represents the time interval of repeated scanning of the same wave position. Except the search task, radar needs to complete other tasks such as tracking. The search frame cycle is related to the priority of the resource and the region in which the radar is searched. Assuming that the search resources are \( SS_0 \), the search priority is \( \rho_0 \), and the search frame cycle is \( T_{f0} \), when the search resources and the priority are \( SS_i \) and \( \rho_i \):

\[
\frac{T_{f0}}{T_{fi}} = \frac{SS_0 \rho_0}{SS_i \rho_i}
\]  

(3)

3.3. SNR of radar echo

Obtained by the radar equation:

\[
R^t = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 kT_{SNR} L}
\]

(4)

Where, \( P_t \) is the transmission power, \( G_t \) is the transmission gain, \( G_r \) is the receiving gain, \( \lambda \) is the wavelength, \( T \) is the effective noise temperature, \( L \) is the system loss, \( R \) is the detection range, and

\[
G_t = \frac{4\eta}{\sin^2(\varphi/2)}
\]

(5)

In Eq. (5), \( \eta \) is the radar array efficiency. Substitute Eq. (5) into Eq. (4):

\[
R^t = \frac{4\eta P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 kT_{SNR} L \sin^2(\varphi/2)}
\]

(6)

When the average transmission power, SNR and normal reverse bandwidth are known as \( P_{t0} \), \( \text{SNR}_0 \) and \( \varphi_0 \):

\[
R^t_0 = \frac{4\eta P_{t0} G_t G_r \lambda^2 \sigma}{(4\pi)^3 kT_{SNR} L \sin^2(\varphi_0/2)}
\]

(7)

Combine Eq. (6) and Eq. (7), we get:

\[
\frac{R^t}{R^t_0} = \frac{P_t}{P_{t0}} \frac{\text{SNR}}{\text{SNR}_0} \frac{\sin^2(\varphi/2)}{\sin^2(\varphi_0/2)}
\]

(8)

3.4. Accumulated detection probability

In the search area of \( R_0 \), the target velocity is \( v \), assuming that the initial tracking distance is \( R_0 \), the Accumulated detection probability is:
\[ P_d = 1 - \prod_{j=1}^{K} (1 - P^{(j)}_d) \]  \hspace{1cm} (9)

In Eq. (9):
\[ \text{SNR} = \frac{R^4 P^s \text{SNR}_p \sin^2(\varphi_i/2)}{R^4 P \sin^2(\varphi/2)} \]  \hspace{1cm} (10)

4. Constraint condition

To ensure the RF stealth performance of the airborne radar, it is necessary to complete the search task while avoiding detection by enemy passive detection systems. The constraints include two parts:

One is the search frame cycle. Once the scanning method is determined, the wave number of the search area is determined. The duration of the beam in each wave position and the search frame cycle should be satisfied:
\[ T_{fi} \geq N_{beams} t_{B_i} \]  \hspace{1cm} (11)

In Eq. (11), \( T_{fi} \) is the search frame cycle of the \( i \)th area, \( N_{beams} \) is wave number, \( t_{B_i} \) is the beam-stay time, and:
\[ t_{ni} = n_i \tau \]  \hspace{1cm} (12)

In Eq. (12), \( n_i \) represents the number of exposures to region \( i \), \( \tau \) is the pulse accumulation width. The other is detection probability. The detection probability of region \( i \) should be satisfied:
\[ P_{di} \geq P_{in} \]  \hspace{1cm} (13)

In Eq. (13), \( P_{di} \) is the expected detection probability.

5. Optimization algorithm

In order to solve the objective function, the particle swarm optimization algorithm is called. An improved particle swarm optimization algorithm is proposed for the traditional one is easy to get into local optimum, the main steps are as follow:

Step 1: Random initializing the position and velocity of each particle.

Step 2: Evaluate the fitness of each particle. The position and fitness of the current particle are stored in pbest of each particle, and stored the pbest which has the optimal fitness value in gbest.

Step 3: update the position and velocity of each particle:
\[ x_{i,j}(n+1) = M / (1 + \exp(-v_{i,j}(n+1))) + (M - 1) \cdot k_1 \cdot r_3 \]  \hspace{1cm} (14)
\[ x_{i,j}(n+1) = M / (1 + \exp(-v_{i,j}(n+1))) + (M - 1) \cdot k_1 \cdot r_3 \]  \hspace{1cm} (15)

Where, \( p_{i,j} \) is the individual extremum, \( p_{g,j} \) is the global extremum, \( w \) is the weight, \( c_1, c_2 \) are the learning factor, \( r_1, r_2 \) are random number between 0 and 1.

Step 4: update the weight. In order to enhance the balance ability and local improvement ability of traditional PSO algorithm, nonlinear dynamic inertia weight coefficient formula is adopted, the expression is as follow:
\[ w' = \begin{cases} \frac{w'_m - w'_m}{w'_m - w'_m} \cdot (f - f_m), & f \leq f_{\text{avg}} \\ w'_m, & f > f_{\text{avg}} \end{cases} \]  

(16)

Where, \( w'_m \) and \( w'_m \) are the maximum and the minimum of the weight, \( f \) is the objective function value of the current particle, \( f_{\text{avg}} \) and \( f_{\text{min}} \) represents the average target value and the minimum target value of the current particle.

Step 5: update the learning factor. The formula is as follows:

\[ c_i(n+1) = c_{i,\text{ini}} + \frac{c_i,\text{fin} - c_{i,\text{ini}}}{N} \cdot (n+1) \]

\[ c_j(n+1) = c_{j,\text{ini}} + \frac{c_j,\text{fin} - c_{j,\text{ini}}}{N} \cdot (n+1) \]

(17)

Where, \( c_{1,\text{ini}}, c_{2,\text{ini}} \) are the original value of \( c_1 \) and \( c_2 \), \( c_{1,\text{fin}}, c_{2,\text{fin}} \) are the final value of \( c_2, c_1 \), \( N \) is maximum number of iterations. The two factors have different changes in the process of optimization over times, in the initial stage, the particles have the larger self learning ability and smaller social learning ability, which can strengthen the global search ability, while in the later stage, particles has great social learning ability and smaller self learning ability, which is conducive to converge to global optimal solusion.

Step 6: update the fitness of the particle and the population. Sorting the fitness of the particles, and particles with the worst performance are picked out, In order to enhance the diversity of particles and avoid falling into the local optimum, gaussian adjustment is made to those particles velocity:

\[ v_{i,j}(n+1) = k_2 \cdot \text{gaussian} \]  

(18)

\( k_2 \) is a constant, \( \text{gaussian} \) is the random number that satisfied the standard gaussian distribution. According to Eq.(15) and Eq. (18) update the particle location and gets the fitness.

Step 7: compared with the optimal fitness, the current position corresponding to the antenna beam distribution sequence is the optimal radar resource allocation decision.

Step 8: if the accuracy requirement is reached (usually the preset precision threshold or iteration number), output the result; otherwise, return to Step 3 to continue the search.

The IPSO algorithm flow chart is as follows:
Figure 2. The IPSO process.

Using the IPSO algorithm, the average power, beam dwell time and beam width is set as particle, according to the formula of SNR, the search frame cycle and wave number of each time are obtained, as well as the detection probability. Under constraint conditions, the minimum value of the objective function is obtained.

6. Simulation result
Parameter setting: average transmission power $P_0 = 6$ kW, SNR0=8dB, the 3dB bandwidth of front normal direction $\phi_0 = 1.8^\circ$, farthest detection range $R_0 = 200$ km, the detection probability of each area is 0.999992, slope angle is $12^\circ$, search resources $SS_0$ account for 80% of total radar resources, the search priority $p_0$ is 0.75, search frame cycle $T_s = 1$ s, search area parameter settings are as follows (the unit is degree):

Table 1. Parameter Settings.

| Area | Upper bound of pitch angle | Lower bound of pitch angle | Upper bound of azimuth | Lower bound of azimuth |
|------|-----------------------------|-----------------------------|------------------------|------------------------|
| A    | $A_1$                      | -30                         | 0                      | -90                    | -30                    |
|      | $A_2$                      | 15                          | 30                     | 0                      | 30                     |
| B    | $B_1$                      | -25                         | 5                      | -80                    | -20                    |
|      | $B_2$                      | 20                          | 35                     | 10                     | 40                     |
| C    | $C_1$                      | -20                         | 10                     | -70                    | -10                    |
|      | $C_2$                      | 25                          | 40                     | 20                     | 50                     |
| D    | $D_1$                      | -15                         | 15                     | -60                    | 0                      |
|      | $D_2$                      | 30                          | 45                     | 30                     | 60                     |
| E    | $E_1$                      | -10                         | 20                     | -50                    | 10                     |
|      | $E_2$                      | 35                          | 50                     | 40                     | 70                     |
To prove the effectiveness of our algorithm, we compared our algorithm with search method based on the largest Detection Probability (LDP) [3], the latter choice the traditional PSO, the total radiation energy and the detection probability compared respectively as shown in Fig. 3 and Tab. 2:

![Figure 3. Radiation Energy Contrast.](image)

| Area | LPSO       | LDP       |
|------|------------|-----------|
| A    | 0.99999968 | 0.99999967|
|      | 0.99999959 | 0.99999953|
| B    | 0.99999961 | 0.99999963|
|      | 0.99999953 | 0.99999954|
| C    | 0.99999945 | 0.99999942|
|      | 0.99999941 | 0.99999940|
| D    | 0.99999938 | 0.99999937|
|      | 0.99999932 | 0.99999931|
| E    | 0.99999953 | 0.99999955|
|      | 0.99999958 | 0.99999957|

It can be seen from Fig.3 and Tab.2, intersects with the LDP algorithm, our algorithm consumes less energy while having better detection performance. The latter maximizes the weighted probability as the objective function, which only considers the constraint of time, and does not consider the effect of radar transmission power on search performance. In this paper, an IPSO algorithm is used to solve the target function for minimum energy consumption, while is can also meet the expected detection probability. The advantage of this algorithm is that the objective function take beam dwell time, average power and beam width into consider, therefore, the constraint is constrained from time domain, energy domain and frequency domain. The IPSO algorithm adaptive adjustment of weight changes, asynchronous learning factor, and introduce compensation factor for blind search, enhance the diversity of particles, the solution is better.

7. Conclusion
In this paper, on the premise of meet the expected detection probability, consider the constrains of time domain, airspace as well as energy domain, we take the minimum energy consumption as objective function. An IPSO algorithm is given, which adaptive adjustment weight, asynchronous change learning factor, and gaussian compensation factor in introduced to search the blind area, which
improve the particle diversity. The simulation result shows, using the IPSO algorithm, radar radiates less energy while the detection probability is improved, which is helpful to improve the radar RF-stealth performance.

References
[1] D.J. Lynch, Introduction to RF stealth, Sci Tech Publishing, 2004: 65-98.
[2] E.P. Phillip, Detecting and classifying low probability of intercept radar, Boston: Artech House, 2009: 1-40.
[3] F. Wang, Low-intercept probability airborne radar signal processing technology, Science press, 2015.
[4] F. Nicolas, J.G.F. Nelson, Investigations on the efficiency of array fed coherently radiating periodic structure beam forming networks, J. IEEE Trans. On Antennas and Propagation, 2011, 59 (2): 493-502.
[5] D.D. Themistoklis, A.M. Stelios, Design of a corner-reflector relatively controlled antenna for maximum directivity and multiple beam forming at 2.4GHz, J. IEEE Trans. On Antennas and Propagation, 2011, 59 (4): 1132-1139.
[6] N.S. Karnik, R. Tulpule, M. Shah, et al, Design, simulation and experimental study of near-field beam forming techniques using conformal waveguide arrays, J. IET Microwaves, Antennas & Propagation, 2010, 4 (2): 162-174.
[7] Z.K. Zhang, J.J. Zhou, Y.B. Tian, et al, Sampling Interval and Power Design Based on RF Stealth, J. Modern Radar, 2012, 34 (4): 19-23.
[8] J. Liao, L. Yu, L.X. Yu, et al, The Radiation Management Control Method of Phased Array Radar Based on LPI, J. Systems Engineering and Electronics Technology. 2011, 33 (12): 2638-2642.
[9] H.Q. Liu, X.Z. Wei, F. Li, et al, Real-time Control Method of Radar Single Radiation Energy under Tracking State Based on RF Stealth, J. Electronic Journal, 2015, 43 (10): 2047-2052.
[10] Z.K. Zhang, J.J. Zhou, F. Wang, et al, A Phased Array Radar Control Algorithm Based on RF Stealth, J. 2012, 34 (11): 2244-2248.
[11] J.G. Wang, Launch DBF Preset Zero Beam Control Technology, J. Modern Radar, 2008, 30 (1): 74-76.
[12] Z.H. Che, A particle swarm optimization algorithm for solving unbalanced supply chain planning problems, J. Applied Soft Computing, 2012, 12 (5): 1279–1287.
[13] X.C. Zhou, Z.X. Zhao, K.J. Zhou, et al, Remanufacturing closed-loop supply chain network design based on genetic particle swarm optimization algorithm, J. Journal of Central South University of Technology, 2012, 19 (2): 482–487.
[14] N. Nedjah, R.D. Calazan, L.D. Mourelle, et al, Parallel implementations of the cooperative particle swarm optimization on many-core and multi-core architectures, J. International Journal of Parallel Programming, 2016, 44 (6): 1173-1199.