Small Evolution Antenna Design Method Based on Dynamic Hill Climbing Algorithm and Orthogonal Experiment

Hui Shi\textsuperscript{1, 2, 3}, Junjie Li\textsuperscript{1, 2, 3} and Zhiming Xie\textsuperscript{1, 2, 3}

\textsuperscript{1}Department of Information Engineering, Shanwei Polytechnic, Shanwei 516600, Guangdong, China
\textsuperscript{2}The Research Institute of Cloud Computing and Data Center Project Design, Shanwei Innovation Industrial Design & Research Institute, Shanwei 516600, Guangdong, China
\textsuperscript{3}The Professional Committee Cloud Computing and Big Data in Higher Vocational College, Higher Education Institute in Guangdong Province, Shanwei 516600, Guangdong, China

shihui0205@163.com

Abstract. Small-scale evolution antennas have the advantages of high gain, wide bandwidth and small size, and have broad application prospects in the aerospace field. Aiming at the complex high-dimensional and dynamic problems of aerial antenna modeling, a dynamic hill-climbing algorithm based on orthogonal design is designed and implemented to simulate and optimize the single-span antenna in high-frequency operation mode. In the optimization problem, this paper defines a new individual comparison mechanism, which can reflect the number of violations of constraints and the degree of violation of each constraint, making the comparison of individuals more reasonable. The antenna simulation results demonstrate the effectiveness and feasibility of using dynamic evolutionary algorithms for antenna design.

1. Introduction

Evolutionary algorithms\cite{1} have been successfully applied to antenna design problems\cite{2-3}. Two of the most attractive examples from the field of antenna design using GA are the X-band antennas for NASA Spacecraft 5 spacecraft\cite{4} and the S-band antennas for NASA lunar atmospheric and dust environment detectors\cite{5}. Aliakbar\cite{6} proposed the use of invasive weed optimization global optimization algorithm to design and optimize printed UWB antennas, using the frequency-dependent cost function with the best weighting factor, has prototyped and optimized two antennas. Chakravarthy et al.\cite{7} applied a new evolutionary computational tool called the Flower Pollination Algorithm (FPA) to linear array synthesis problems and evaluated the performance of amplitude-based and amplitude-based methods. Jiao\cite{8} models the antenna design problem as a constrained optimization problem, introduces a framework to transform the constrained optimization problem into an equivalent dynamic constrained multi-objective optimization problem, and applies a dynamic constrained multi-objective evolutionary algorithm to solve the transformed antenna design problem. The robustness and stability of the antenna design. Y Y Fan\cite{9} designed an improved jDE (i-jDE) evolution algorithm based on adaptive parameter adjustment differential evolution (jDE) algorithm. The distributed orthogonal test method was combined with high-precision electromagnetic simulation software to balance the accuracy of
In order to reduce the size of the antenna and improve the working bandwidth, Y S Ma [10] used hybrid genetic algorithm and differential evolution algorithm to optimize the antenna loading and matching network. A short-wave width whip antenna was actually fabricated. In this paper, the single antenna design under high frequency condition is modeled, and the dynamic hill climbing algorithm based on orthogonal design is designed to optimize the antenna. A constrained optimization method in antenna design is proposed. The antenna simulation results demonstrate the effectiveness and feasibility of using dynamic evolutionary algorithms for antenna design.

2. Evolutionary Antenna Mathematical Model

2.1. Target Technical Indicators of Antenna Design

In this paper, a single-span antenna is designed as an example. The dynamic antenna climbing algorithm [11] is used to simulate the line antenna. The target technical indicators are as follows:

- Transmission frequency: 8470 MHz
- Receiving frequency: 7209.125MHz
- Polarization mode: right circular polarization
- Input impedance: 50Ω
- Gain pattern: \( \geq -5 \text{dBic}, \ 0^\circ \leq \theta < 40^\circ, \ 0^\circ \leq \phi \leq 360^\circ \); \( \geq 0 \text{dBic}, \ 40^\circ \leq \theta \leq 80^\circ, \ 0^\circ \leq \phi \leq 360^\circ \).
- Standing wave ratio: transmitting frequency \(<1.2\), receiving frequency \(<1.5\)
- Geometric size: diameter \(<15.24\text{cm}\)
- Height \(<15.24\text{cm}\)
- Antenna quality: \(<165\text{g}\)

The antenna design requires that each segment of the wire does not need to be too long (maximum length does not exceed half wavelength), nor can it be too short (the minimum length specified in this paper cannot be less than \(1/100\) of the wavelength). The angle between adjacent wires should not be too narrow. Too narrow will result in unstable results calculated by the electromagnetic calculation software (the angle is not more than \(20^\circ\)). According to the above technical indicators, the constraints that need to be considered in the evolution design include the following aspects:

- Antenna structure: height \(<15.24\text{cm}\); diameter \(<15.24\text{cm}\);
- Standing wave ratio: transmitting frequency \(<1.2\); receiving frequency \(<1.5\);
- Gain: \( \geq -5 \text{dBic}, \ 0^\circ \leq \theta < 40^\circ, \ 0^\circ \leq \phi \leq 360^\circ \); \( \geq 0 \text{dBic}, \ 40^\circ \leq \theta \leq 80^\circ, \ 0^\circ \leq \phi \leq 360^\circ \).
- Length of each segment of the wire: \(1 / 100 \leq l \leq \text{half wavelength of the wavelength}\)
- Adjacent wire angle: \( \alpha \geq 20^\circ \)

Under the constraints of the above antenna electrical parameters, the evolution goal of this antenna is to optimize the design of a single-arm line antenna, so that the smaller the better the quality, the smaller the standing wave ratio, the better the direction. The greater the gain, the better.

Considering the feasibility of practical operation and based on relevant theoretical research, this paper adopts the coding scheme of real evolution algorithm. The initial feeder is a short wire with the starting point of the feeder at the origin and the direction along the positive Z axis. \(r\) is the radius of the wire and \(Z_0\) is the length of the feeder. The wires are connected end to end. Each wire can be described as: radius, and the wire end point coordinates \((x, y, z)\) are the three components of the coordinate. The corresponding chromosomes are \((r, Z_0, x_1, y_1, z_1, \ldots, x_n, y_n, z_n)\), where \(r\) and \(Z_0\) are fixed in the algorithm.

2.2. Mathematical Model of Antenna Optimization Design

Based on the above three elements of the antenna optimization problem, we can establish a corresponding formal mathematical model, which can be described as:

- Minimize \( T_{\text{VSWR}} (r_0, r_1, x_1, y_1, z_1, \ldots, x_n, y_n, z_n) \)
- Minimize \( R_{\text{VSWR}} (r_0, r_1, x_1, y_1, z_1, \ldots, x_n, y_n, z_n) \)
- Minimize \(-T_{\text{Gain}}\theta\phi (r_0, r_1, x_1, y_1, z_1, \ldots, x_n, y_n, z_n)\)
- Minimize \(-R_{\text{Gain}}\theta\phi (r_0, r_1, x_1, y_1, z_1, \ldots, x_n, y_n, z_n)\)
- Satisfy To:
3. Antenna Optimization Calculation Model Design

3.1. Antenna Design Optimization Problem
In this paper, the electromagnetic calculation software NEC is used as the antenna performance evaluation tool. Due to this optimization problem, the design variables will exceed 20 dimensions, the number of targets exceeds 2000, and the number of constraints exceeds 2000. Therefore, how to overcome "many goals" is a major difficulty in algorithm design [12]. Here are mainly the following technical means to deal with the "many goals" problem:

- Converting multi-objective optimization problems into single-objective optimization problems overcomes the "many goals" difficulty, which can be achieved by appropriately weighting the targets of the constraints;
- Design a dynamic sequential comparison selection operation based on relaxation-dynamic shrinkage techniques;
- Improve the performance of dynamic evolution algorithm calculations, such as diversity and convergence.

Figure 1 depicts the overall framework for solving antenna design problems based on dynamic evolutionary algorithms.

3.2. Antenna Optimization Model Suitable for Dynamic Single-objective Evolutionary Algorithm
For practical applications, the main optimization objectives of this evolutionary antenna are as follows:

- Sum of transmit frequency sampling point gains: $f_1 = \sum_{i=0}^{355} \sum_{j=0}^{80} (-T_{\text{Gain}_{ij}})$
- Sum of the gains of the receiving frequency sampling points: \( f_2 = \sum_{i=0}^{355} \sum_{l=0}^{80} (-R_{Gain_i}) \)
- Transmit frequency standing wave ratio: \( f_3 = T_{VSWR} \)
- Receive frequency standing wave ratio: \( f_4 = T_{VSWR} \)

Add all the goals and turn the multi-objective optimization problem into a single-objective optimization problem:

\[
f = \sum_{i=0}^{355} \sum_{l=0}^{80} (-T_{Gain_i}) + \sum_{i=0}^{355} \sum_{l=0}^{80} (-R_{Gain_i}) + T_{VSWR} + T_{VSWR}
\]  
(1)

The constraints are given in section 2.2. Single target optimization problem, its general form:

- \( Q \)
- Minimize \( f(\bar{x}) \)
- Subject to
  - \( g_i(\bar{x}) \leq 0 \quad i = 1, ..., q \)
  - \( h_i(\bar{x}) = 0 \quad i = q + 1, ..., m \)
  - \( X = \{\bar{x} = (x_1, x_2, ..., x_n) | l_i \leq x_i \leq u_i\} \)
  - \( \bar{l} = (l_1, l_2, ..., l_n) \)
  - \( \bar{u} = (u_1, u_2, ..., u_n) \)

\( \bar{x} \) is the decision vector, \( X \) is the decision space, and \( \bar{l}, \bar{u} \) is the upper and lower bounds of the decision space.

For equality constraints, they are often converted to inequality constraints:

\[
|h_i(\bar{x})| - \delta \leq 0, i = q + 1, ..., m
\]  
(2)

If the solution \( \bar{x} \) satisfies both \( |h_i(\bar{x})| - \delta \leq 0 \) and \( g_i(\bar{x}) \leq 0, i = 1, 2, ..., q, (i = q + 1, ..., m) \) then the decision vector \( x \) is considered feasible.

The constraint conditions in the single-objective optimization form above are utilized as the following: the individual of the initial group can be made, and then the constraints are gradually reduced as the evolution progresses until all the constraints are satisfied. This process can be formalized as a dynamic optimization problem in the general form as follows.

- \( Q(t) \)
- Minimize \( f(\bar{x}) \)
- Subject to
  - \( g_i(\bar{x}) \leq \epsilon_{g_i}(t) \quad i = 1, ..., q \)
  - \( h_i(\bar{x}) = \epsilon_{h_i}(t) \quad i = q + 1, ..., m \)
  - \( X = \{\bar{x} = (x_1, x_2, ..., x_n) | l_i \leq x_i \leq u_i\} \)
  - \( \bar{l} = (l_1, l_2, ..., l_n) \)
  - \( \bar{u} = (u_1, u_2, ..., u_n) \)

In the above formula, \( \lim_{t \to \infty} \epsilon_{g_i}(t) = 0, \lim_{t \to \infty} \epsilon_{h_i}(t) = 0 \). With the parameter \( t \to \infty \), the dynamic form \( Q(t) \) will approximate the static form \( Q \) in the expression. It is worthwhile to record this approximation process as \( \lim_{t \to \infty} Q(t) = Q \). Suppose the parameter \( t \) in the dynamic form (5) is the evolution algebra of the evolutionary algorithm, and let the evolutionary algorithm solve \( Q(t) \) in the \( t \) generation, then, based on the solution of the \( t \) generation, solve \( Q(t+1) \) in the \( t+1 \) generation, then with \( t \to \infty \), the evolutionary algorithm finally solves the constrained optimization problem \( Q \). Based on this idea, we use dynamic evolutionary algorithms to solve antenna optimization problems.

### 3.3. Multi-Constraint Processing

The specific implementation method: initially, the constraint condition is sufficiently relaxed, so that the initial group is all feasible. As the evolution progresses, the constraints are gradually reduced and the individuals of the current group are almost relaxed. When the evolutionary operation is terminated, the relaxation constraint is finally contracted back to satisfy the original constraints, and the individual relaxation and feasible characteristics of the group make the individuals of the last group almost feasible. Default function:

- \( G_i(\bar{x}, t) = \max\{\epsilon_{g_i}(t), |g_i(\bar{x})|\}, i = 1, ..., q \)
- \( H_i(\bar{x}, t) = \max\{\epsilon_{h_i}(t), |h_i(\bar{x})|\}, i = q + 1, ..., m \)

\( G_i(\bar{x}, t) \) and \( H_i(\bar{x}, t) \) are the default function for the multi-objective optimization problem.
Calculate the relative default value of the constraint function:

- \[ \bar{g}_i(\vec{x}, t) = \frac{G_i(\vec{x}, t)}{\text{Max}G_i(t)}, \ i = 1, \ldots, q \]
- \[ \bar{h}_i(\vec{x}, t) = \frac{H_i(\vec{x}, t)}{\text{Max}H_i(t)}, \ i = q + 1, \ldots, m \]
- \[ \text{Max}G_i(t) = \max_{\vec{x} \in P(t)} \{G_i(\vec{x})\} \]
- \[ \text{Max}H_i(t) = \max_{\vec{x} \in P(t)} \{H_i(\vec{x}, t)\} \]

\( P(t) \) is the \( t \) generation group. \( \text{Max}G_i(t) \) is the maximum default value of the constraint \( g_i(\vec{x}) \) in the \( t \) generation group \( P(t) \), and \( \text{Max}H_i(t) \) is the maximum default value of the constraint condition \( h_i(\vec{x}) \) in the \( t \) generation group \( P(t) \).

Two individual \( (\vec{x})_1, (\vec{x})_2 \) comparison algorithms:

- \[ v_1 = \sum_{i=1}^{q} G_i((\vec{x})_1, t) + \sum_{i=q+1}^{m} H_i((\vec{x})_1, t); \]
- \[ v_2 = \sum_{i=1}^{q} G_i((\vec{x})_2, t) + \sum_{i=q+1}^{m} H_i((\vec{x})_2, t); \]
- \[ v_1 < v_2 \iff (\vec{x})_1 \text{ better than } (\vec{x})_2, \]
- \[ v_1 > v_2 \iff (\vec{x})_1 \text{ worse than } (\vec{x})_2 \]
- \[ v_1 = v_2 \land f((\vec{x})_1) < f((\vec{x})_2) \iff (\vec{x})_1 \text{ better than } (\vec{x})_2 \]
- \[ v_1 = v_2 \land f((\vec{x})_1) = f((\vec{x})_2) \iff (\vec{x})_1 \text{ competitive to } (\vec{x})_2 \]
- \[ v_1 = v_2 \land f((\vec{x})_1) > f((\vec{x})_2) \iff (\vec{x})_1 \text{ worse than } (\vec{x})_2 \]
- \[ \varepsilon_{\text{ad}}(t) = \text{Max}G_i(0)/C^t \]
- \[ \varepsilon_{\text{ud}}(t) = \text{Max}H_i(0)/C^t \]

C is a constant of \( > 1 \) and is used to control the degree of relaxation of the equality constraint. In the algorithm of this paper, \( C=1.02 \).

4. Dynamic Evolutionary Algorithm Design For Antenna Optimization

The flow based on the ODHC dynamic evolution algorithm is shown in Figure 2:

![Figure 2. Process based on ODHC algorithm](image-url)
// Start climbing
REPEAT
// Learn past search results
FOR for each past peak stored in the archive
Create a niche W and store peaks in the center of each niche
Calculate the representation of the niche in each niche W
    Niche W moves to a new peak
ENDFOR
// Detect new peaks
REPEAT
Create an initial niche E randomly
Niche E moves to a new peak
Insert E into the archive
// Dynamic order selection operation
IF archive is full
Perform dynamic sequential selection operations in learning niche W and detecting niche E (considering diversity)
ENDIF
UNTIL meets termination conditions
Note: Performing a dynamic sequential selection operation (taking into account diversity) in learning niche W and detecting niche E means that if the distance between two peaks in the archive is less than the predefined limit \(\varepsilon_1\), it is randomly deleted. Either of these two niches, otherwise, based on the “relaxation-dynamic shrinking technique”, delete the niche that holds the shortest peak in the archive. The orthogonal design method was used in the calculation of the representation of niche \([13]\).

5. Experimental Simulation

5.1. Parameter Settings
The parameters for the algorithm when setting the antenna are as follows:
- Initial size of niche: \(d_1, d_2, \ldots, d_8\).
- Orthogonal array is used to calculate the niche representation, the number of rows of the orthogonal array: \(M = Q\).
- The number of peaks stored in the archive (the number of niches, which is equivalent to the population size in the evolutionary algorithm): \(K = 100\).
- In order to maintain the initial value of the diversity of peaks in the archive: \(\varepsilon_1 = 0.006\).
- Minimum shrinkage limit for niches: \(\varepsilon_2 = 0.001\).
- Control the degree of relaxation of the equality constraint: \(C = 1.02\).
In the experiment, each side of the search space is equally divided into 30, thus halving the search space, and the default initial size of the niche is the size of each of the aliquots \(Q_1 = Q_2 = \ldots = Q_N = 30\). Experiments have shown that this allows the objective function in each niche to have at most 1 peak in it. According to \(M = Q'\) and \(P = (Q'-1)/(Q-1)\), when \(Q\) is selected, a smaller prime number is selected. If \(Q\) is too large, the orthogonal matrix \(L_M(Q')\) will be too large, so it will greatly increase the amount of statistical calculation in the orthogonal design, and let \(Q = 5\) in the algorithm.
5.2. Simulation Results
In this paper, the electromagnetic field numerical calculation simulation software 4NEC2 based on the moment method is used. In the experiment, the population size was 100 (the number of peaks that can be stored in the archive body: K=100), the evolution was 5000 generations, and the ODHC algorithm was used for 500,000 evaluations.

Figure 3 shows the final antenna simulation structure. Figure 4 shows that the VSWR of the antenna basically meets the target technical specifications: the transmission frequency <1.2 at the transmission frequency: 8470 MHz; the VSWR reception frequency <1.5 at the reception frequency: 7209.125 MHz. Figure 5 and Figure 6 show that the antenna gain basically meets the target technical index: the gain pattern: ≥-5dBic, 0°≤θ<40°, 0°≤φ≤360°; ≥0dBic, 40°≤θ≤80°, 0°≤φ≤360°.

Figure 3 In this case simply justify the caption so that it is as the same width as the graphic.

Figure 4. Antenna standing wave ratio curve.

Figure 5. Maximum and minimum gain curves of the antenna at the transmission frequency

Figure 6. Maximum and minimum gain curves of the antenna at the receiving frequency
6. Conclusion
In this paper, the characteristics of genetic algorithm and antenna optimization design simulation are studied. The coding scheme of single-strand antenna structure model is proposed and the mathematical optimization of antenna optimization is carried out. The antenna design optimization problem of "many targets, many constraints" is transformed into "many constraints". The single-objective optimization problem of condition is designed to simulate and optimize the single-span antenna under high-frequency operation mode by designing a dynamic hill-climbing algorithm based on orthogonal design. For the problem of constrained optimization in antenna design, this paper defines a new individual comparison mechanism, which can reflect the number of violations of constraints and the degree of violation of each constraint, making the comparison of individuals more reasonable. The antenna simulation results demonstrate the effectiveness and feasibility of using dynamic evolutionary algorithms for antenna design.

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