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Design of Brownian Particle Swarm Algorithm for Optimizing Antenna Layout on Unmanned Boat

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Abstract: In response to the problem that traditional particle swarm optimization algorithms are difficult to search for optimal solutions due to the complex constraints of unmanned boat platform in antenna coupling layout, a Brownian particle-inspired Brownian particle swarm optimization algorithm is proposed. The new algorithm embeds Brownian particles into the traditional particle swarm optimization algorithm, and the Brownian particles perform irregular exploration movements without being constrained by the constraints in the traditional algorithm, enabling exploration within discontinuous feasible domains. Using Friis transmission equation as the objective function to solve antenna coupling degree of unmanned boats, solving results obtained using Brownian particle swarm optimization algorithm are superior and more efficient compared to those obtained using traditional particle swarm optimization algorithms.

1. Introduction

The development of modern science and technology has led to the widespread application of various electronic and electrical equipment in people's daily lives. Not only is the quantity and variety of electronic and electrical equipment constantly increasing, but they are also rapidly developing towards miniaturization, digitization, high speed, and networking. When electronic and electrical equipment is working normally, it often generates useful or useless electromagnetic energy, which may affect the environment where other devices, systems, and organisms are located. Electromagnetic compatibility issues are becoming increasingly prominent. Unmanned boat platforms are equipped with a large number of antennas as well as electronic and electrical equipment.[1] Not only can coupling occur between antennas affecting communication, but the electromagnetic energy radiated outward by antennas and high-frequency electronic devices can also affect sensitive electronic equipment. Solving the problem of antenna interference on unmanned boat platforms is more difficult and important than ever before.

The Friis transmission equation for dipole antennas is extended for antennas mounted on unmanned boats. And for the unique spatial constraints of the unmanned boat platform, inspired by Brownian motion[2], a particle doing Brownian motion is proposed to improve the exploration ability of the particle. And the Friis transmission equation is used as the objective function, and the traditional particle swarm algorithm is compared with the Brownian motion particle swarm algorithm to prove the feasibility of the new particle swarm algorithm.

2. Fundamentals of Antenna Coupling for Unmanned Boat Platforms

2.1. Antenna Interference Modelling for Unmanned Boat Platforms

In order to achieve unmanned, unmanned boats are equipped with many antennas for communication. According to the different frequencies and functions, the antennas on unmanned boats can be divided into 156MHz AIS (Automatic Identification System) antennas, 902-928MHz remote digital transmission antennas and 1428-1448MHz broadband communication antennas. In the narrow space of the unmanned boat, there have to be several equipment working at the same time. When the frequencies between the antennas are the same or close to each other, the proximity of the antennas placed close to each other leads to strong coupling[3]. This will result in the signal received by one party's equipment containing a large number of interference signals from another device, giving rise to the problem of co-address interference, as shown in the specific interference schematic in figure 1. If the signal received by the equipment is affected, it will greatly reduce the performance of the receiver as well as the quality of communication, reduce the communication distance, and in serious cases, lead to the loss of control of the unmanned boat.

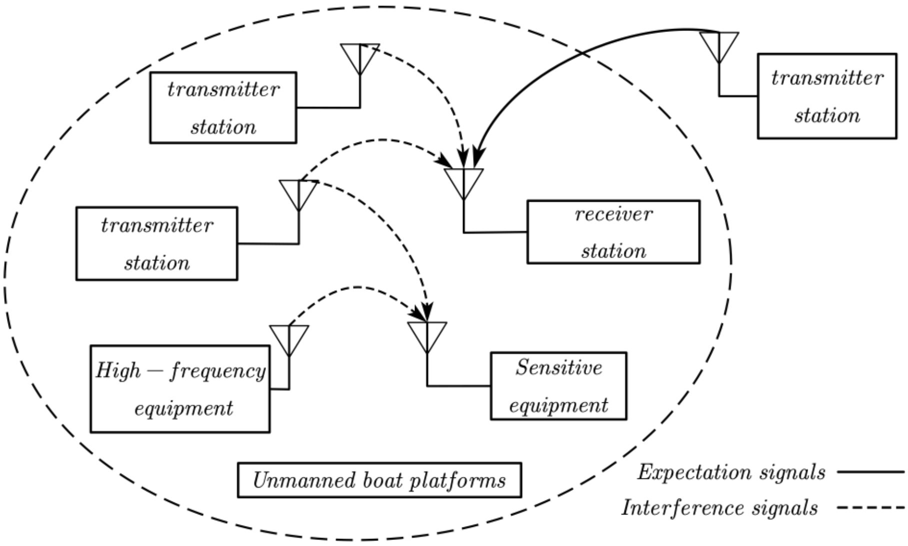

Figure 1: Antenna interference modelling for unmanned boat platforms

2.2. Two-port Network

Taking the coupling of a pair of transceiver antennas as an example, according to the transmission network theory in microwave engineering[4], the antenna coupling can be equated into a two-port model, as shown in Fig 2.

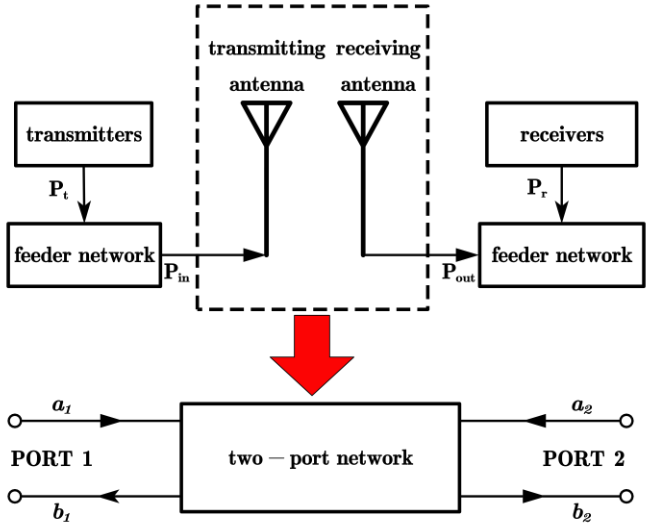

Figure 2: Two-port network

The coupling is defined as:

$$C = 10\log\left(\frac{P_{out}}{P_{in}}\right) \tag{1}$$

Where C is the coupling degree in dB; P_{in} is the net input power of the transmitting antenna after the actual transmit power P_t of the transmitter is attenuated by the feed network; and P_{out} is the net output power of the receiving antenna. The S-parameter matrix of the two-port network is:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \tag{2}$$

Where a_1 and a_2 denote the incident waves at port 1 and port 2, respectively, and b_1 and b_2 denote the reflected waves at port 1 and port 2, respectively. The output power of the receiving antenna at port 2 is:

$$P_{out} = \frac{1}{2}|b_2|^2 - \frac{1}{2}|a_2|^2 \tag{3}$$

The input power of the transmitting antenna at port 1 is

$$P_{in} = \frac{1}{2}|a_1|^2 - \frac{1}{2}|b_1|^2 \tag{4}$$

Assuming that both port 1 and port 2 are in the impedance matching state, i.e., the values of a_2 and b_1 are 0. From equations (2) (3) (4), we can see that:

$$\frac{P_{out}}{P_{in}} = \frac{\frac{1}{2}|b_2|^2 - \frac{1}{2}|a_2|^2}{\frac{1}{2}|a_1|^2 - \frac{1}{2}|b_1|^2} = \frac{|b_2|^2}{|a_1|^2} = |S_{21}|^2 \tag{5}$$

From equations (1) and (5), we can see that:

$$C = 10\log\left(|S_{21}|^2\right) \tag{6}$$

Where S_{21} can be simulated by full-wave electromagnetic simulation software or measured by vector network analyser.

2.3. Friis Transmission Equation for Half-wave Dipole Antennas

Although the coupling between antennas can be measured and simulated using a model of a two-port network, these calculations are performed when the antennas are already installed in a fixed position. Moreover, for a platform of the size of an unmanned boat, a large number of grids will be divided in the simulation software for calculation, which has the problem of large memory and calculation time occupation and is not easy to be implemented by programming. Therefore, it is more convenient and practical to use the Friis transmission equation[5] as the objective function to calculate the coupling between antennas in occasions where the computational accuracy is not particularly high. The Friis transmission equation in free space can be written as:

$$\frac{P_{out}}{P_{in}} = \frac{G_r G_t \lambda^2}{(4\pi R)^2} \tag{7}$$

where G_r and G_t denote the maximum gain of the receiving and transmitting antennas, respectively; λ is the wavelength of the transmitting antenna; and R is the distance between the phase centres of the transceiver antennas.

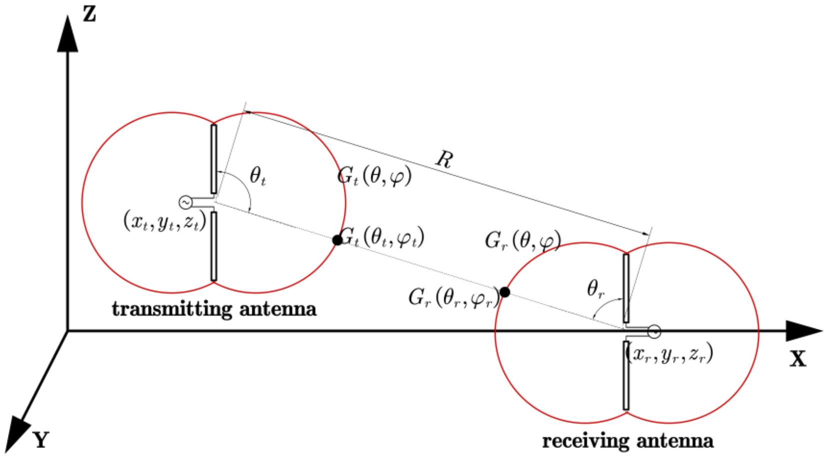

Figure. 3: Coupled dipole antenna modelling

Most of the antennas installed on unmanned boats are whip antennas, which can be equated using a dipole antenna, and the Friis transmission equation for a quarter-wavelength dipole antenna as shown in figure 3 can be written as:

$$\frac{P_{out}}{P_{in}} = \left(\frac{1.64}{4\pi}\frac{\lambda}{\sqrt{(x_r-x_t)^2+(y_r-y_t)^2+(z_r-z_t)^2}} \frac{\cos^2\left(\frac{\pi}{2}\cos\left(\arccos\frac{z_r-z_t}{\sqrt{(x_r-x_t)^2+(y_r-y_t)^2+(z_r-z_t)^2}}\right)\right)}{\sin^2\left(\arccos\frac{z_r-z_t}{\sqrt{(x_r-x_t)^2+(y_r-y_t)^2+(z_r-z_t)^2}}\right)}\right)^2 \tag{8}$$

Where x, y, z denote the coordinates of the antenna in the Cartesian coordinate system, and the following tables t and r denote transmission and reception, respectively.

3. Algorithmic Optimisation

3.1. Particle Swarm Algorithm

Particle swarm algorithm is a kind of evolutionary computation technology based on group intelligence[6], the individual particles are volume-free particles in the multidimensional search space, the position of the particles represents the potential solution of the optimization problem, and the flight speed of the particles determines the direction and step length of the search. The particle's speed change in the search space can be dynamically adjusted according to its own and its companion's flight experience, gradually moving to a better area, and finally arriving at the optimal position in the entire search space, the velocity update and position update equations are as follows:

$$\boldsymbol{v}_i^{(t+1)} = \omega \boldsymbol{v}_i^{(t)} + c_1 \mathbf{r}_1 (\boldsymbol{p}_i - \boldsymbol{x}_i^{(t)}) + c_2 \mathbf{r}_2 (\boldsymbol{p}_g - \boldsymbol{x}_i^{(t)}) \tag{9}$$

$$\boldsymbol{x}_i^{(t+1)} = \boldsymbol{x}_i^{(t)} + \boldsymbol{v}_i^{(t+1)} \tag{10}$$

where $\mathbf{v}_i^{(t)}$ is the velocity vector of particle i at iteration t, $\mathbf{v}_i^{(t)} = (v_{i,1}^{(t)}, \cdots, v_{i,d}^{(t)})$; i is the index of the particle in the swarm, where $i \in \{1, 2, ...G\}$; G is the size of the population; d is the dimension of the optimization problem; t is the index of the iteration, where $t \in \{1, 2, ..., T\}$; T is the total number of iterations; ω is the inertia weight factor; c_1 is the cognitive factor; c_2 is the social factor; $\mathbf{r}_1$ and $\mathbf{r}_2$ are random vectors; $\mathbf{x}_i^{(t)}$ is the position vector of particle i at iteration t, where $\mathbf{x}_i^{(t)} = (x_{i,1}^{(t)}, \cdots, x_{i,d}^{(t)})$; $\mathbf{v}_i^{(t)}$ is the velocity vector of particle i at iteration t, where $\mathbf{v}_i^{(t)} = (v_{i,1}^{(t)}, \cdots, v_{i,d}^{(t)})$; $\boldsymbol{p}_i$ is the best position vector of particle i from the 1st iteration to the tth iteration, which is the individual best solution, $\boldsymbol{p}_i = (p_{i,1}, \cdots, p_{i,d})$; $\boldsymbol{p}_g$ is the best position vector of the entire population from the 1st iteration to the tth iteration, which is the global best solution, $\boldsymbol{p}_g = (p_{g,1}, \cdots, p_{g,d})$.

In formula (9), the next velocity is affected by the current velocity, cognitive factor (c1), and social factor (c2). In formula (10), the next position is the sum of the current position and the next velocity.

3.2. Brownian Particle Swarm Algorithm

In order to make the particle swarm with stronger exploration ability, make more particles break through the constraints and the influence of individual cognitive factor and social cognitive factor. Inspired by Brownian motion, some of the particles in the swarm are made to move irregularly by constantly changing their direction and speed. These Brownian motion particles tend to explore more and are not limited by constraints. In order to be able to make these Brownian particles do Brownian motion, two new parameters are proposed:

α: $\alpha \in (0,1)$, represents the proportion of Brownian particles in the population. For example, $\alpha = 0.2$ means that there are 20% Brownian particles in the population. α is equal to 1 and the whole population is Brownian.

β: $\beta \in (0,1)$, which represents the proportion of Brownian particles changing direction in Equation (11). For example, $\beta = 0.3$ means that the Brownian particle has a 30% probability of changing direction.

With the new parameters, the Brownian particle calculates velocity using Equation (11) instead of the updated velocity Equation (9) and, independent of social and cognitive factors, moves forward regardless of the feasibility of the position reached.

$$v_{i,j}^{(t+1)} = D(r_{4,j},\beta)S(v_{i,j}^{(t)})r_{3,j}V_{max}, j = 1, \cdots, d \tag{11}$$

where i is the index of the Brownian particle, β is the parameter of the Brownian particle, $r_{4,j}$ and $r_{4,j} \in (0,1]$ are random variables, $D(r_{4,j},\beta) \in \{-1,1\}$ is the directional function that $D(r_{4,j},\beta)=1$ $D(r_{4,j},\beta) \leqslant \beta$, and $D(r_{4,j},\beta) = -1$ when $r_{4,j} > \beta$, and $S(v_{i,j}^{(t)})$ is the sign of the variable $v_{i,j}^{(t)}$.

The Brownian particle swarm algorithm is the addition of Brownian particles to the traditional particle swarm, and there are two kinds of particles, traditional particles and Brownian particles, in the particle swarm at the same time.

4. Simulation Verification

In this paper, two remote control and digital transmission antennas with frequencies of 902-928 MHz on the unmanned boat are used as an example for simulation and verification, and the central operating frequency of the antennas is at 915MHz. When the spacing between the two antennas varies with the multiples of the antenna's operating wavelengths, the change of the coupling between the two antennas is shown in figure 4, which shows that the coupling near the central frequency of the antennas is higher and the antenna coupling gradually decreases with the increase of the distance. increases and the coupling degree of the antenna decreases with the increase of the distance.

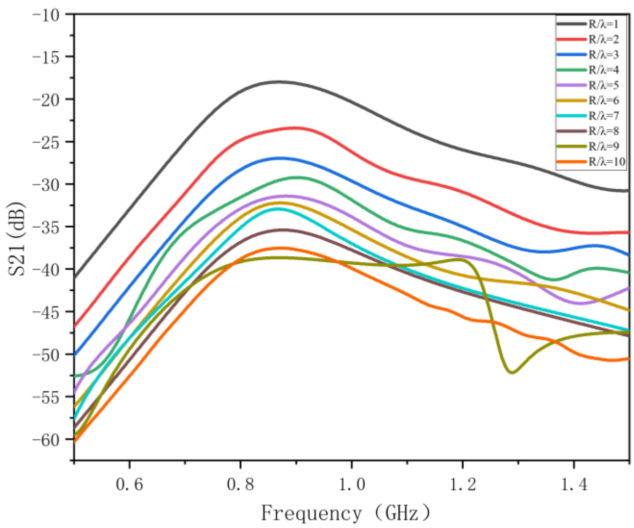

Figure 4: Antenna coupling simulation value

Selecting the central operating frequency of the antenna, the results of the coupling calculation using the improved Friis transmission equation are compared with the results of the simulation as shown in figure 5, which shows that the calculated values are more consistent with the simulated values, and the improved Friis equation can be used for the construction of the objective function of the particle swarm algorithm.

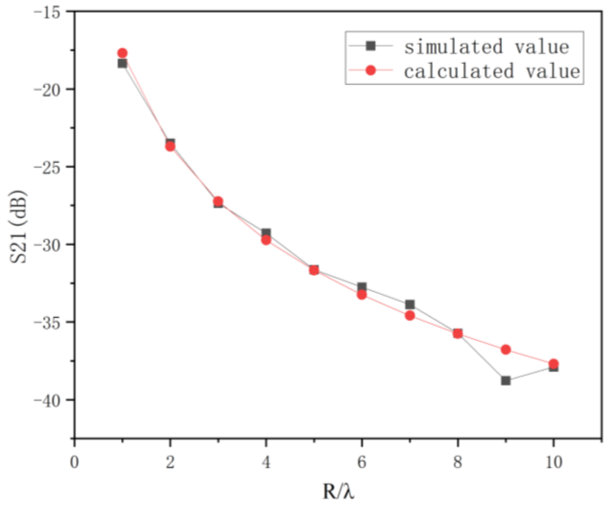

Figure. 5: Comparison of calculation and simulation

The feasible domain of the particle swarm algorithm is determined based on the near-field constraints of the Friis transport equation and the actual mountable area of the unmanned boat platform. The obtained region range is shown in Table 1.

Table 1 Antenna installation area

Regin	Realm
Regin1	0≤x≤500，-1000≤y≤0，0≤z≤200
Regin2	250≤x≤750，250≤y≤750，1900≤ z ≤2000
Regin3	1000≤x≤4000，-900≤y≤900，0≤z ≤200, $\sqrt{(x-4000)^2+y^2+z^2} \geq 340$
Regin4	1200≤x≤1700，-250≤y≤250，1800 ≤z≤1900

The variation of the coupling degree calculated by the two algorithms with the number of iterations is shown in figure 6. Position coordinates of the final solution of the traditional algorithm are (1000, 900, 200) with a coupling degree of -18.92 dB, and the position coordinates of the improved final solution are (613.4, 650.4, 2000) with a coupling degree of -21.51 dB. The Brownian Particle Swarm Algorithm converges faster than the traditional particle swarm algorithm and the coupling degree obtained is lower.

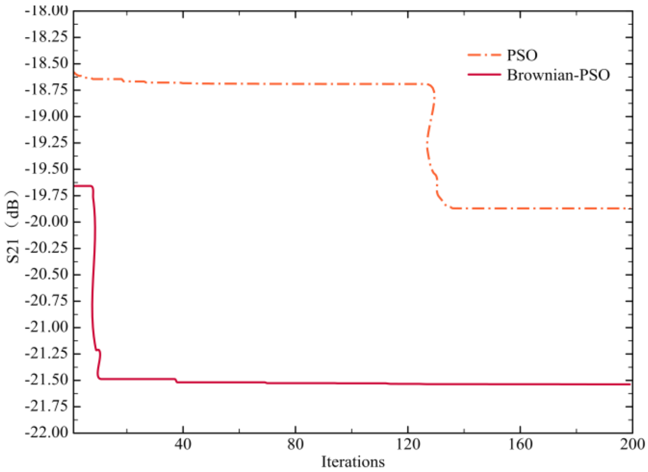

Figure. 6: Coupling comparison chart

5. Conclusion

In this study, Friis transmission equation is used as the calculation method of antenna coupling degree, and a Brownian particle swarm algorithm inspired by Brownian motion is proposed, which is simple to apply and the Brownian particles are easy to be embedded into the traditional particle swarm algorithm. Through the comparison of simulation and calculation, it can be determined that the coupling degree results calculated by the improved Friis transmission equation are more accurate. When the traditional particle swarm algorithm is used to lay out the antenna of the unmanned boat, due to the complexity of the constraints on the antenna placement position of the unmanned boat platform, the algorithm is trapped in the local optimal solution. And the Brownian particles can break through the constraints and explore freely between different feasible domains, and their exploration ability is stronger. Through 100 rounds of test comparisons, it is proved that the Brownian particle swarm algorithm is better than the traditional particle swarm algorithm to get out of the local optimal solution and find the global optimal solution. It solves the problem that traditional particle swarm is difficult to get the optimal solution in the face of the complex constraints of antenna placement on unmanned boat platforms, and provides a better choice for antenna installation and placement.

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