



Research on UAV Swarm Interference Based on Improved Invasive Weed Optimization Algorithm

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Abstract. With the continuous development of Unmanned Aerial Vehicle (UAV) technology, autonomous control systems and communication technologies, the combat mode of UAV has gradually shifted from single-platform to multi-platform operation adapting to complex battlefield environment, i.e. the mode of operation has gradually developed to 'swarm'. On this basis, UAV swarm carried jamming equipment can conduct large-scale cooperative jamming on radar. UAV swarm, with low launch power, can be deployed in the enemy depth and thus obtain the advantages of distance and spatial distribution. This paper focuses on the formation of effective cooperative jamming beams for UAV swarm. Due to the application background of UAVs, the distance between the UAV array antennas is much larger than the half-wavelength, resulting in the occurrence of grating lobes and the energy is difficult to concentrate. And the above problems are solved through sparse array synthesis, which use improved invasive weed optimization (IWO) algorithm to optimize position of UAVs. And the simulation results show that sparse array synthesis can solve the problem of energy concentration and grating lobes.

Keywords: Invasive weed optimization algorithm · Radar interference · UAV swarm

1 Introduction

With the increasing complexity of modern battlefield environment, radar electronic warfare, as an important part of electronic warfare, influences the outcome of the war [1]. As the radar adopts various anti-interference measures such as low sidelobe level, pulse compression and so on, the corresponding challenge to radar jammer is put forward [2]. Traditional high-power concentrated jamming has disadvantages such as large cross-section area, large transmitting signal power and relatively remote distance to the enemy, which will lead to problems such as easy detection by the enemy radar, negative impact on the equipment of the own side and poor electromagnetic compatibility [3]. Under this circumstance, a specific combat pattern for UAV swarm is raised, namely using UAV swarm carrying jamming equipment to carry out close-range main lobe jamming on target radar. UAV swarm cooperative jamming has many advantages such as large number, small volume, small cross-section area and so on.

With the continuous development of aircraft technology, Unmanned Aerial Vehicles (UAVs) have become the focus of research in the world. The UAV is the aircraft without a human pilot, the flight of UAV may operate with various degrees of autonomy: either under remote control by a human operator or autonomously by onboard computers [4]. And with the fast development of UAV, the combat mode of UAV has gradually shifted from single-platform to multi-platform operation adapting to complex battlefield environment, i.e. the mode of operation has gradually developed to ‘swarm’. The UAV swarm has a great advantage in pattern of operation, mainly focus on the following aspects: (1) The advantage of low-cost, UAV swarm can be equipped a large number UAVs. (2) The advantage of scale quantity, a large number of low-cost UAV swarm have launched saturation attack on the enemy, making it difficult for the enemy to effectively defend and even the risk of failure of its air defense system. The United States NPS (Naval Postgraduate School) has experimented with UAV swarm, an Aegis Combat System confronts a swarm of UAVs consisting of 5 to 10, the result of the simulation is that 2.8 of every 8 UAVs can effectively break through air defense interceptions. If the number of UAVs is expanded to 20 and 50, the interceptor system can only intercept 7 or so, which greatly improving the UAV’s penetration capability [5]. (3) The advantage of combat effectiveness, the UAV swarm has the advantage of cost and quantity scale, which will inevitably bring the advantage of combat effectiveness. (4) The superiority of the system, the UAV swarm system has a strong “self-healing” ability. If some UAVs are shot down by enemy fire, the team adapts by reconfiguring optimally continue the mission with the surviving assets [6].

This paper uses UAV swarm carrying jamming equipment for interfering to the enemy radar. However, under the background of UAVs, Using UAVs to focus on one direction interference has following problems, including: ① The energy of a UAV array element is difficult to concentrate and the power is not enough. Therefore, this paper proposes to use the UAV swarm to carry antenna to form antenna array to send interference signals. ② Because of the volume of the UAV itself, spacing between adjacent UAV require 30–50 m, but the signal frequency is usually at GHz. And it will result in the occurrence of grating lobes and the interference energy is difficult to be concentrated. To solve above problems, this paper proposed to consider the UAVs as the sparse array to focus on the interference energy to concentrate energy.

For the sparse array synthesis problem, evolutionary optimization algorithms have been considered and successfully applied to this problem. And the various approaches have been developed such as genetic algorithm (GA) [7], ant colony optimization (ACO) [8], simulated annealing algorithm (SA) [9], particle swarm optimization (PSO) [10] and so on. The invasive weed optimization (IWO) algorithm is popular of evolutionary optimization algorithms and it is getting much attention due to its efficiency and simplicity. And it has been successfully applied to several optimization problems, such as antenna design [11] and array synthesis [12]. This paper selects IWO algorithm to optimize the position of UAV swarm, and two problems that weak local search ability and slow convergence speed in this algorithm were improved, i.e. the standard deviation formula was improved to enhance the convergence speed and the hill climbing method was improved the local search ability. On the basis of the above improvement, the improved invasive weed optimization (IIWO) algorithm was

proposed and selected to optimize the position of UAV swarm along with array optimization models.

The paper is structured as follows: Sect. 1 is the introduction part of this article; Sect. 2 is the signal model and optimal model of the UAVs array antenna; Sect. 3 introduces the IIWO algorithm; Sect. 4 is the simulation results.

2 Signal Model Based on UAVs

In this model, suppose the UAV is used to carry antenna array element, every UAV carries identical antennas working together as a single big UAVs antenna array. The radio frequency power from the UAV is fed to the individual array element with the specific excitation relationship through the device controlled by a computer system, so that the radio waves from the separate UAV array element add together to increase the radiation in a desired direction, while cancelling to suppress radiation in undesired directions. And the interference model of UAV swarm is show in the Fig. 1.

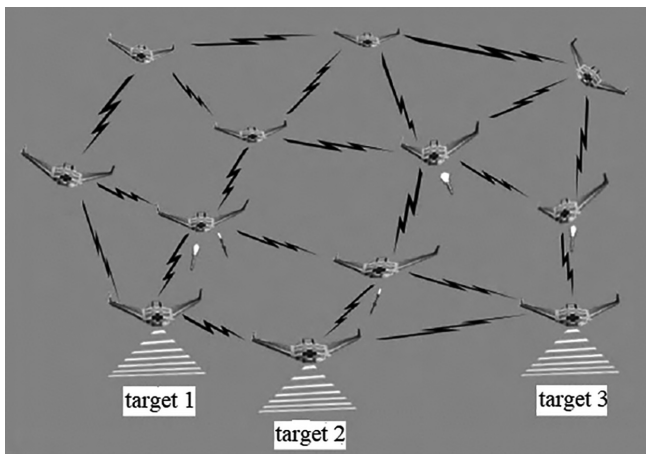


Fig. 1. UAVs interference model

In the practical, for safety reasons, the distance between adjacent UAV elements is 30 to 50 m, but the working frequency is usually GHz, which means that the distance is very small. For this problem, this paper puts forward the sparse array to solve it. Sparse array means that the distances between adjacent UAV elements are different and not constrained in $\lambda/2$. The UAV element positions are randomly distributed within the UAVs aperture [13].

Compared to linear and other planar arrays, circular array can provide 360° azimuth and better controls main lobe direction, at the same time, beam shape, antenna gain and mutual coupling performance maintenance or basically maintain owing to the symmetry of the circular array. These advantages make circular antenna array has been

widely used in the field of sonar, radar and satellite communication system [14]. So circular UAVs antenna array is discussed to analyze the problem.

The radiation pattern of an individual antenna element is $f(\theta, \varphi)$, θ and φ are respectively the elevation angle and azimuth angle. Assuming that the array element is an ideal omnidirectional antenna element, the result is that $f(\theta, \varphi) = 1$. The conventional array synthesis is based on the product principle of the directional diagram. Total field radiated by this array in xy plane is expressed as follows:

$$F(\theta, \varphi) = \sum_{n=1}^N I_n e^{j[kR \sin \theta \cos(\varphi - d_n) + \beta_n]} \quad (1)$$

The radiation pattern of the entire array is only related to the array factor $F(\theta, \varphi)$. Where

- N : the number of UAVs
- λ : the wavelength
- R : the radius of the circular UAVs array antenna
- I_n : incentive amplitude of the UAV
- β_n : incentive phase of the UAV
- $k = 2\pi/\lambda$: the wavenumber
- d_n : the position of the UAV

When the array main lobe is pointed in the (θ_0, φ_0) , the phase can be written as:

$$\beta_n = -kR \sin \theta_0 \cos(\varphi_0 - d_n) \quad (2)$$

If the elevation angle $\theta = 90^\circ$, then (1) maybe written as:

$$F(\varphi) = \sum_{n=1}^N I_n e^{jkR[\cos(\varphi - d_n) - \cos(\varphi_0 - d_n)]} \quad (3)$$

The number of UAVs is N , and the minimum interval between adjacent UAVs is dc to make the UAV safety. In order to minimize the peak side lobe (PSLL), the optimal model is proposed:

$$\begin{aligned} & \text{find } \mathbf{d} = [d_1, d_2, \dots, d_N] \\ & \min \{ \text{PSLL}(\mathbf{d}) \} \\ & \text{s.t. } d_{i+1} - d_i \geq dc \quad 1 \leq i \leq N - 1 \end{aligned} \quad (4)$$

The PSLL is expressed:

$$\text{PSLL} = \max \left| \frac{AF(\theta_{sl}, \varphi_{sl})}{\max(AF(\theta, \varphi))} \right| \quad (5)$$

Where the denominator is the maximum of the main beam in the direction, and $(\theta_{sl}, \varphi_{sl})$ is the sidelobe region excluding the main beam. The optimization model of formula (3) shows that by optimizing the position of the UAVs can get a good result for interference. And the optimization of location problem is a typical global optimization problem, therefore, using the intelligent optimization algorithm to solve it.

3 Proposal Algorithm

Mehrabian and Lucas proposed the invasive weed optimization (IWO) algorithm for solving continuous optimization problems in 2006 [15]. Each invading weed takes the unused resources in the field and grows to the weed and produces new seeds, independently. The number of new seeds produced by each weed depends on the fitness of that weed in the colony. Those weeds that have better adoption to the environment and take more unused resources grow faster and produce more seeds. The new produced seeds are randomly spread over the field and grow to the weeds. And only those weeds with better fitness can survive and produce new seeds.

3.1 Classical Invasive Weed Optimization Algorithm (IWO)

IWO algorithm is a swarm intelligence optimization algorithm [16]. It mimics the process of colonizing and distributing behavior of weeds. Each weed in the algorithm is a latent solution for the position of the UAVs. Each weed corresponds to a fitness value determined by the fitness function. The algorithm is composed of the following parts:

1. Reproduction. Each member of the weeds is allowed to produce seeds depending on its own, as well as the colony's lowest and highest fitness, so that the number of seeds produced by a weed increases linearly from lowest possible seed for a weed with worst fitness to the maximum number of seeds for a plant with best fitness.
2. Spatial Distribution. Weed seeds produced by normal distribution spread around his father generation. The standard deviation for a particular iteration can be given as follows:

$$\sigma = \frac{(iter_{\max} - iter)^n}{(iter_{\max})^n} (\sigma_{\text{initial}} - \sigma_{\text{final}}) + \sigma_{\text{final}} \quad (6)$$

Where

- n : non-linear harmonic factor
- $iter_{\max}$: maximum number of evolution
- σ_{initial} : maximum standard deviation
- σ_{final} : minimum standard deviation

3. Competitive Exclusion. The weeds in a colony will reproduce fast and all the produced plants will be included in the existing colony, until the number of plants in the colony reaches a maximum value P_{\max} . The steps 1 to 3 are repeated until the maximum number of iterations has reached.

3.2 Improved Invasive Weed Optimization Algorithm (IIWO)

Over the past decades, the IWO method has been widely applied to array synthesis. And this algorithm allows all of possible candidates to participate in the reproduction process. The disadvantages of the IWO are that weak local search capability in the late iteration, slow convergence speed, and easy to fall into local optimum [17]. Therefore, this paper improves the algorithm for the above problems.

(1) Improvement of standard deviation formula

In the standard algorithm, the standard deviation in the process of spatial diffusion is only related to iteration. In this paper, the standard deviation formula is improved that not only related to iteration, but also related to the fitness value of the individual. The formula is as follows:

$$\sigma_n = \frac{|f - f_{best}|}{f_{best}} * \sigma \quad (7)$$

Where, f is the fitness value of the current individual, and f_{best} is the best fitness value in the current iteration, σ is the standard deviation, σ_n is the improved standard deviation. In the process of seed diffusion, the standard deviation function not only changes with the change of iteration times, but also is related to the fitness value of the individual. The larger the fitness value of the individual, the smaller of standard deviation will be, i.e. the seeds produced by individuals with better fitness are distributed in a smaller range, while the seeds of individuals with poor fitness are distributed in a larger range. In this way, the convergence speed of the algorithm can be improved and better computing effect can be obtained.

(2) Improvements to local search

As a global search algorithm, one of the disadvantages of the IWO is that weak local search capability in the late iteration. In this case, the hill climbing method can be combined with IWO to improve the local search capability. The main idea of the hill climbing algorithm is: take the adjacent point and the current point for comparison each time, take the better of the two as the next step of climbing [18]. The algorithm firstly should have an initial point which can be obtained by the final result of IWO algorithm, then in the initial position around the calculation of random point fitness value, compared with the initial point, in order to better as a new initial point, repeated operation, until find meet the conditions of point, no change or several iterations ends operations.

The flow chart representing the IIWO algorithm is been shown in Fig. 2.

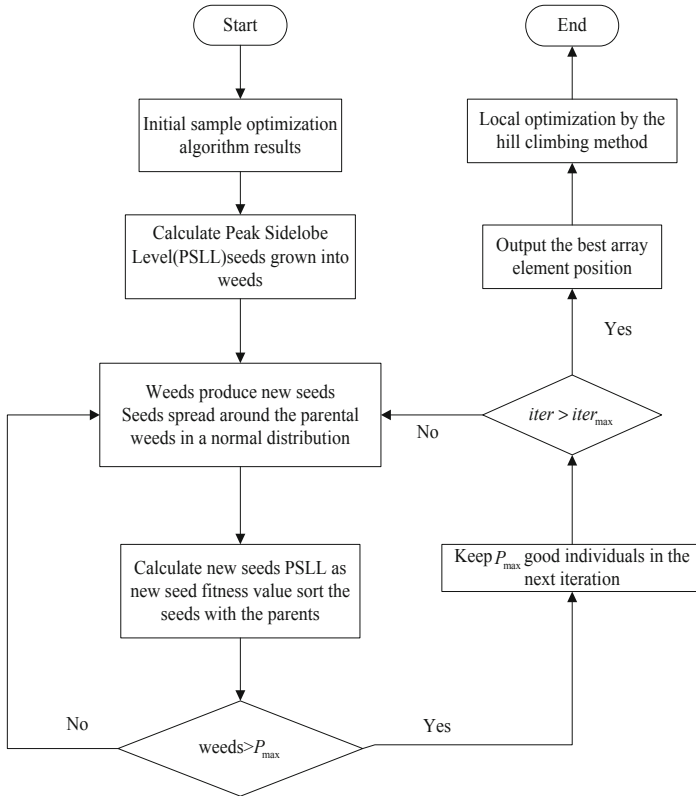


Fig. 2. IIWO algorithm flow chart

4 Simulation Result

This algorithm is simulated and tested in MATLAB-2016 software. The distance between adjacent UAV elements is 30 to 50 m. At the same time, the number of experimental clusters of UAVs is $N = 50$, and the signal frequency is set to 3.5 GHz, the iterations of algorithm is 100, and the radar is in the 150° direction of the UAVs. Under the above conditions, the experiment is conducted. Compare the following results:

1. The experiments give the performance of the differential evolution (DE), firefly algorithm (FA), bat algorithm (BA), invasive weed optimization (IWO) algorithm and improved invasive weed optimization (IIWO) algorithm.
2. The experiments give the performance of the IIWO algorithm.
3. The simulation experiments are conducted to solve the problems of position offset.

4.1 Performance Test of Different Algorithm

Under the above simulation conditions, the experiments were conducted to test under different intelligent optimization algorithms, the experimental results are as follows.

Table 1. Comparison of optimal effects of different 5 algorithm

| Index | DE | FA | BA | IWO | IIWO |
|---------------------------|-----------|--------------------|-------------------|--------------------|--------------------|
| 5 | -1.824 | -1.951 | -1.970 | -2.068 | -2.573 |
| 10 | -4.778 | -4.921 | -5.047 | -5.155 | -5.896 |
| 50 | -11.218 | -11.733 | -11.834 | -12.502 | -13.404 |
| Optimization of time (50) | 50.0130 s | 1 min 14.0370 s | 1 min 1.0670 s | 1 min 45.0570 s | 1 min 56.9010 s |

Table 1 is the performance comparison for different algorithms, from it we can see that the IIWO algorithm of this paper can obtain better optimization results than others, but its convergence speed is relatively slow. The reason is that the improvement of local search by hill climbing algorithm is added, which lengthened the convergence time. Figure 3. shows convergence characteristics of 5 algorithms.

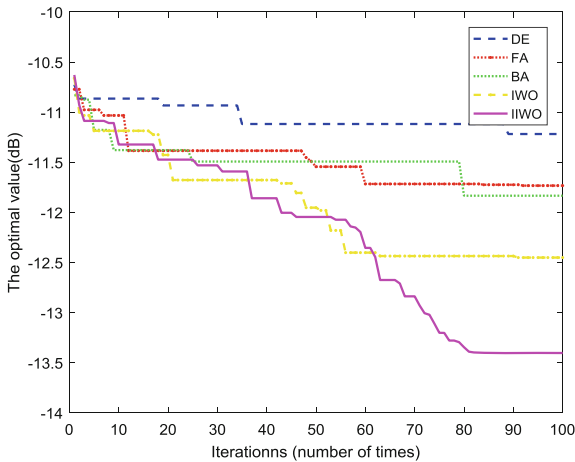


Fig. 3. Convergence characteristics of 5 algorithms (50 Array elements)

4.2 Performance Test of IIWO

Under the same simulation conditions, select IIWO algorithm for simulation, and the results are shown as follows. Figure 4 is the Normalized radiation patterns with IIWO algorithms, Fig. 5 is the distribution map of UAVs after IIWO algorithm optimization, and Fig. 6 is the fitness value convergence characteristic curve and its average curve of five independent simulation experiments of IIWO algorithm, from which it can be seen that the IIWO algorithm has relatively stable convergence.

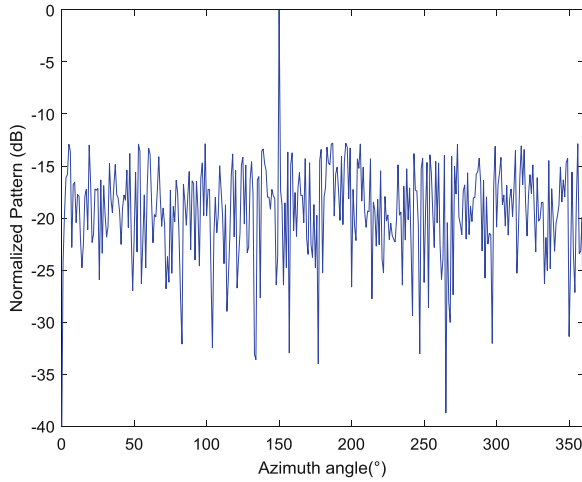


Fig. 4. Normalized radiation pattern of IIWO algorithm

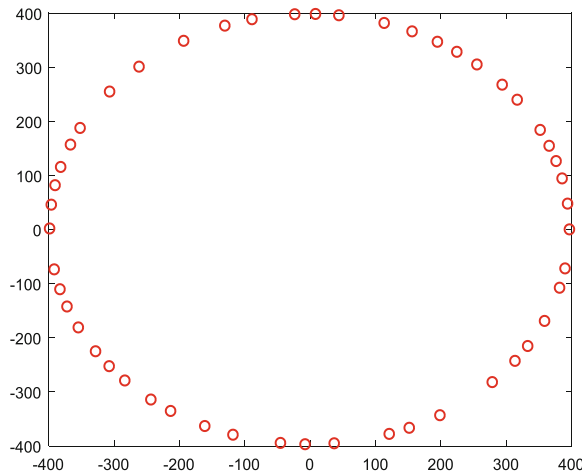


Fig. 5. The distribution of UAVs

4.3 Performance Test of the Simulation Under Position Offset

There will be a variety of factors in the flying process of UAV swarm, which will lead to the problem of position offset. And the simulation experiments are conducted to solve the problems of position offset. The basic simulation parameters are as follows: the number of UAVs $N = 50$; the number of offset $N_o = 15$; the maximum offset distance $d_{\max} = 20$ m; the excursion position and angle are randomly set, and the results are shown as follows (Fig. 7).

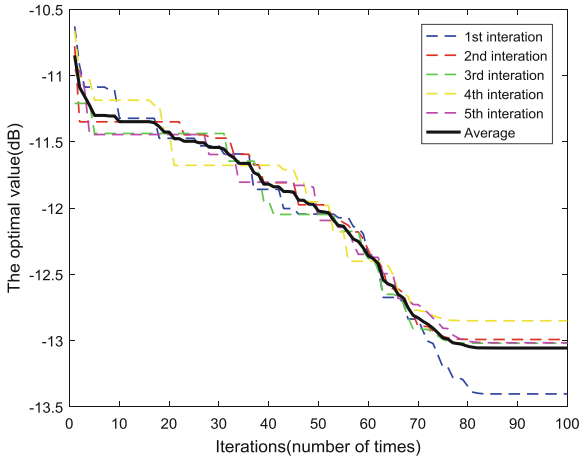


Fig. 6. Convergence characteristics of IWO algorithm

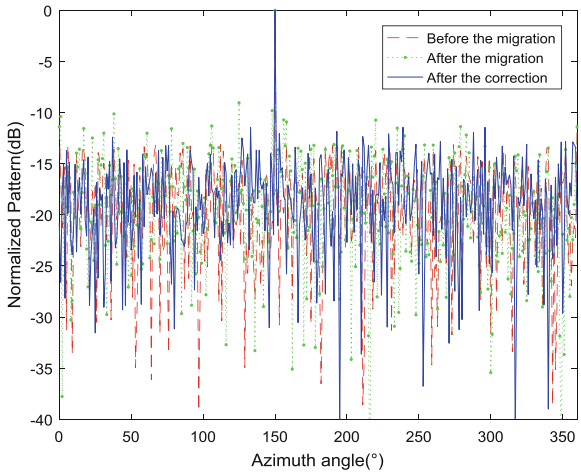


Fig. 7. Normalized radiation pattern

According to the simulation results, the PSL value before offset is -13.1227 dB, and it drops to -9.0462 dB after offset, the value reaches -11.4374 dB by IWO algorithm correct. This optimization algorithm can be used to effectively adjust the position of UAV at any time to form a better interference beam. Figure 8 is shows the UAV distribution before and after the offset and after the correction.

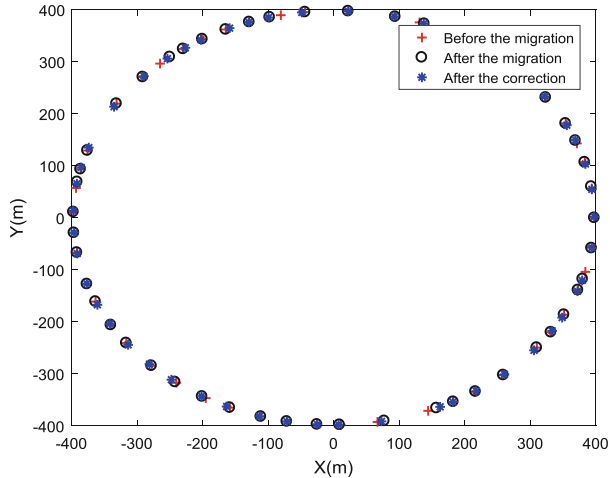


Fig. 8. The distribution of UAVs

5 Conclusions

As an emerging and combat pattern, UAV swarm is exerting immeasurable influences on future wars. This paper analyzes on the advantages of the UAV swarm and the concept of cooperative interference, on the basis of this puts forward the specific model and implementation scheme, i.e. it is using UAV swarm carry jamming equipment to conduct large-scale cooperative jamming on radar. This paper researches the layout scheme of UAV swarm cooperative interference combined with the actual situation of UAV swarm, and presents the optimization model, and selects IIWO algorithms to optimize the position of UAV swarm along with array optimization models. The simulation experiments are conducted to solve the problems of position offset which may occur in the actual interference process, and the correction experiments are analyzed by the IIWO algorithm. Through the analysis of the above results, the proposed implementation scheme can achieve expected result in the actual simulation, and can solve the problem of energy concentration and grating lobes.

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