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Contents

Research on Autonomous Fire Control Attack of UAV for Dynamic Kill Net

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Abstract. The traditional attack mode of unmanned aerial vehicle (UAV) can not meet the needs of the complex battlefield. Based on the analysis of the development of UAV fire control technology, this paper puts forward the design idea of autonomous multi-target high-efficiency damage of UAV and the key technical points to be solved. With the continuous improvement of computing power, efficient and reliable autonomous unmanned attack becomes possible.

Keywords: Dynamic kill net · Autonomous attack · High-efficiency damage · Plug and play

1 Introduction

Unmanned aerial vehicle (UAV) plays a specific role in the operation of precision strike, and the traditional control attack method can no longer meet the current battlefield demand. Giving full play to the role of the command, management and control center of the autonomous combat mission of the fire control mission system, and continuously improving the autonomous mission capability level of the UAV are the only way for the UAV to develop in the opposite precision strike direction.

Unmanned aerial vehicle fire control task system is no longer a simple weapon release and guidance parameter calculation, but is composed of airborne and ground task subsystems, involving information processing and action decision system composed of several tightly coupled processes for each link of observation-judgment-decision-strike [1, 2].

2 Development of UAV Fire Control Technology

Traditional unmanned fire control system mainly operates around weapon platforms. Each platform acquires battlefield information by itself and controls firepower to complete combat tasks, which limits the ability of information exchange and sharing between platforms and affects the overall combat effectiveness. Under the new joint combat system, platform capabilities distributed in different time and space are required to realize functional integration with combat tasks as the core, so that the robustness and tactical flexibility of the combat system can be greatly improved. Driven by such functional requirements, the architecture of fire control system will inevitably develop

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towards flattening, decentralized decision-making and self-synchronization, that is, distributed and intelligent collaboration is the inevitable trend of fire control system development in the new era.

Fire control originates from military confrontation, so its concept naturally has vitality, and it changes with the continuous development of technology and operational concept. Some experts and scholars use Aircraft Fire Control of the US Navy in 1944, Principles of Fire Control of the Massachusetts Institute of Technology in 1959, General Theory of Fire Control System of the US Department of Defense in 1996, the US Department of Defense Joint Publication JP1-02, Dictionary of Military Language and Related Terms of the US Department of Defense in 2009 and the National Fire Control Forum (NFCS) in 2006–2020 as materials. From this, we can see that the American fire control thought is the combination of new operational concepts and new technologies, and the technology and operational factors it contains are constantly evolving. Since 2015, the idea of fire control has evolved into the concept of kill chain. That is, an Engagement process can be represented by Kill Chain (i.e. F2T2EA = Find, Fix, Track, Target, Engage, Assess [3, 4]), as shown in Fig. 1.

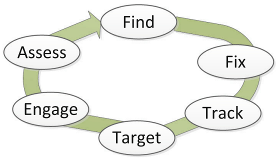

Fig. 1. Schematic diagram of killing chain

Conceptually, American fire control research has expanded from focusing only on aiming and attacking in the Principles of Fire Control in 1959 to focusing on the whole killing chain. In the fire control forum, it has covered topics such as “combat identification”, “intelligence, surveillance-reconnaissance” and “sensor resource management/sensor-data fusion”.

It is precisely because of the continuous development of operational concepts and technologies that the industry is paying more and more attention to the concept of aviation firepower and command and control system, which covers an integrated closed-loop large-scale system composed of sensors, aviation weapons, weapon control, operational management and command and control functions, which is used to complete the detection, identification and tracking of enemy targets in the air, ground and Water surface/underwater, and evaluate the environmental situation of aircraft and targets through data fusion and information processing. Operational management, command and control, aiming, attacking and guiding all kinds of weapons carried by the carrier according to the distribution of fire power, and evaluating the operational effectiveness are more in line with modern fire control thought.

Nowadays, in the face of the operational needs of cooperative system, whether it is manned combat aircraft or unmanned aerial vehicle, a design concept recognized by the industry is that the fire control system adopts distributed architecture, based on automatic/intelligent information management of sensors, weapons and links, to ensure that the OODA operational loop can be completed cooperatively by different units. In the concrete implementation process, each combat unit is deployed in a vast geographical space in a highly decentralized manner, using networked sensors to generate and utilize highly shared battlefield situation in real time, and adopting "general" algorithm to automatically generate cooperative operational decision-making, so as to realize self-organizing synchronization and coordinated action, thus completing the operational command intention.

Facing the specific design of UAV fire control system engineering, it must be emphasized that the completion of weapon preparation and launch is only one of the most basic functions of fire control, and the deep integration of fire control and combat tasks has become the guiding ideology of fire control system design in the new period.

In the future battlefield, UAV will carry the basic tasks in the whole operation, including maneuver tasks, reconnaissance tasks and attack tasks. At the same time, it has the function of data link communication, and can communicate with commanders or other unmanned combat units to master the current battlefield situation. The following figure shows the flow chart of this scenario based on dynamic killing net (Fig. 2).

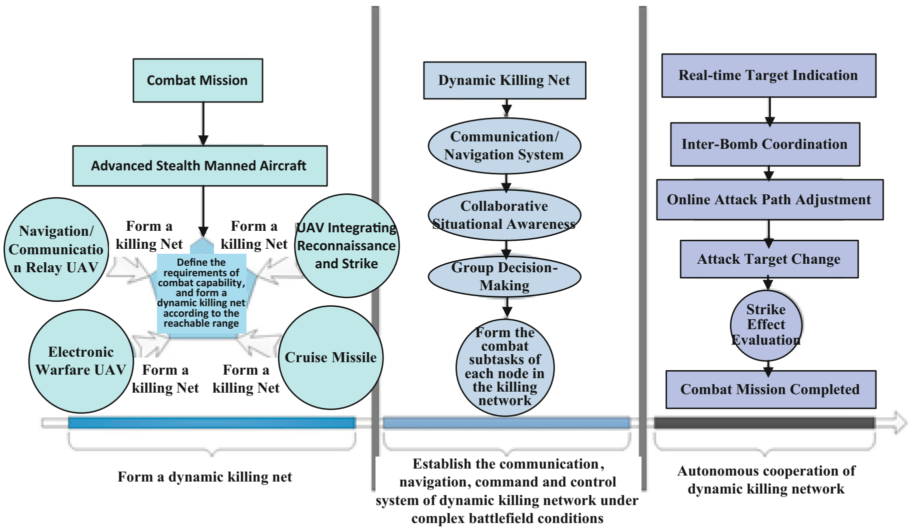

Fig. 2. Flow chart of dynamic kill network operation scenario

3 Autonomous Fire Attack Planning Under Dynamic Killing Network

3.1 Design Idea

Under the unified framework of comprehensive operations, the autonomous attack capability in each mission scenario can be realized.

a) Rapid integration of newly added weapons: when new weapons are integrated, they have the ability to quickly form combat effectiveness without changing the existing hardware resources or changing or slightly changing the status of existing platform software.
b) Automation and intelligence: it can realize the highly automated and intelligent decision-making in the whole battle process from sensor detection to weapon engagement, and realize the self-coordination and self-synchronization of force weapons.
c) Autonomous attack design: realize the "efficient" combination of autonomous task capability and human-in-loop control, and realize task-oriented autonomous task management based on human supervision and key authorization.
   1. In view of the fact that the airborne processing capacity is far lower than the ground processing capacity and the current machine optimization decision is difficult to reflect the commander's fighting will, when the link is normal and the ground-air interaction delay meets the safety and mission requirements, besides the real-time special information related to flight safety is automatically executed by the airborne system according to the predetermined strategy, the battlefield situation judgment, target confirmation and weapon release decision are handed over to the ground processing and ground operator intervention.
   2. When the link is abnormal and automatically silences, the UAV can make decisions that meet the operational requirements according to the given autonomous authority level [5, 6]. For example, in the two links of "target confirmation" and "weapon release", conditions are required to authorize the UAV.
d) Reasonable information flow planning: integration of platform resources and combat resources, all-round information guarantee, and realization of information processing, distribution and acquisition on demand.
e) Natural human-computer interaction: promote the natural and friendly human-computer interaction of combat system to an important position.

3.2 Assumption of Autonomous Attacking Multiple Ground Targets by Chance

a) Scenario assumption
   1) Battlefield environment: There are several enemy radar positions between us and the enemy, and field air defense systems are deployed around enemy fortifications.
   2) Characteristics of attack targets: several fortifications temporarily built by the enemy.

3) The ground command center, UAV formation and reconnaissance satellite are interconnected by data link.

b) Operation and evaluation process
   1) The ground mission control station always controls and monitors the UAV formation mission process.
   2) When the communication link between the ground station and the UAV is unblocked:
      - The ground control station receives the targets and threats detected by UAV formation through data link, obtains the information obtained by intelligence stations, command posts, reconnaissance satellites, etc., and generates a comprehensive situation map.
      - According to the threat on the attack path, the mission planning seat of the ground control station generates the route plan with the least threat influence, and generates the attack plan and the backup attack plan according to the attack priority, target characteristics, target distribution and weapon carrying characteristics. The generated attack plan includes missile-target matching, attack entry point, preparation point, weapon delivery channel and exit point, etc. The ground station distributes the attack plan to the combat UAV in real time through the data link.
   3) When the communication link between the ground station and the combat drone fails:
      - When the link goes down, the drone goes into autonomous mode. The UAV fleet leader strategy is planned in advance from the ground, and the UAV fleet leader takes over and makes route planning and attack planning independently.
      - The leader makes his own judgment by the situation of the battlefield shared by his wingman. According to the threat on the attack path, the route planning with the least influence of the threat is generated. According to the attack priority, the target characteristic, the target distribution situation, carries the weapon characteristic to generate the attack plan. Each wingman Task Execution Program is distributed through a data link between the long wingmen.
   4) Target attack: the combat drone starts from the attack entry point, and real-time fire control calculation is carried out to guide the combat drone to prepare weapons, enter the release channel and release weapons, so as to realize multi-weapon and multi-target efficient fire attack.
   5) Damage assessment: the UAV carries the sensor to capture the damage effect of the target, and transmits the damage image to the ground station and the ground mission seat through the data link for assessment, so as to accuse the UAV of making a second strike (Fig. 3).

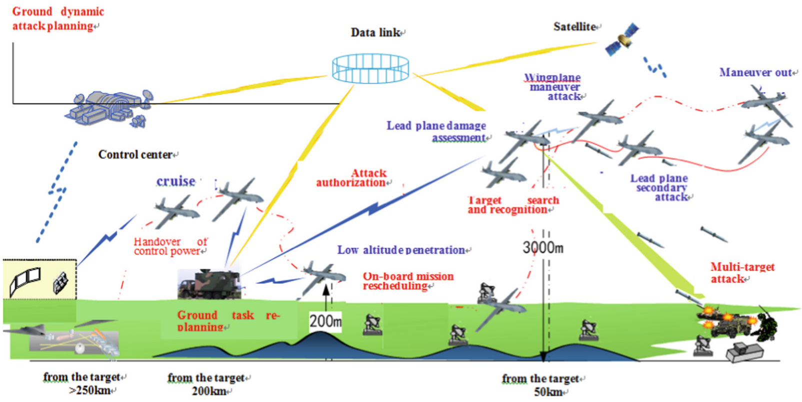

Fig. 3. Assumption of autonomous attacking multiple ground targets by chance

3.3 Key Technical Points to be Solved

a) Efficient air-to-ground multi-target damage technology
   1) Entering the combat area at one time, attacking multiple targets at the same time greatly improves the aircraft's opposite attack capability, improves the aircraft's own survivability, and makes the combat mission get twice the result with half the effort.
   2) The technical difficulty lies in the comprehensive consideration of whether there are priority targets, geometric distribution of targets, weapon characteristics, etc. in the calculation of launching channel of multi-target attack on the ground. The calculated launching area should not only cover all targets as much as possible, but also give full play to the performance of the projectile, so as to achieve accurate damage to the mission targets in the shortest possible time.

b) Integrated autonomous attack process design
   1) The detection load of UAV is limited by the target irradiation angle, overhead tracking, target movement and other constraints, which reduces the attack time window for moving targets, may miss the best attack profile, or even fail to constitute the attack conditions.
   2) Independently evaluate the optimal weapon delivery conditions, automatically form attack guidance, evaluate and compensate the target maneuver, automatically complete weapon aiming and safe projection and guidance, and expand the attack window of UAV.
   3) The technical difficulty lies in the highly reliable confirmation of attack targets and the independent and reliable control of launching.

c) Plug and play technology of fire control system
   1) In order to meet the operational requirements of future combat aircraft, the functions of fire control mission system are becoming more and more complex, the state of attached weapons is constantly changing (including existing and newly developed weapons), and the iterative upgrade and maintenance of products are becoming more and more complex. It is a solution to develop

mission system by using open, modular synthesis and rapid integration technology, and realize the modularization and plug-in of mission system functions, which can solve the contradiction between the existing platform capabilities and the increasing operational mission requirements.

2) Through the system architecture based on hierarchical design, the general modularity of each function of fire control management is realized, and the attack process of various weapons is realized. The system can realize the agile integration of newly added weapons or other functions through modular plug-ins, parameter configuration, system adjustment, etc. without changing the software and hardware. That is, fire control functions are designed as small-grained plug-ins and reside on common processing resources, forming a plug-in pool. The plugins in the plug-in pool are scheduled by parameter configuration to form the fire control function of a specific weapon. For a new weapon, if not all its fire control functions are included in the pool, add a plug-in and put it in the plug-in pool. Through the plug-in fire control function, it can greatly shorten the time to form combat effectiveness.

4 Summary

This paper analyzes the development of unmanned aerial vehicle fire control technology, puts forward the design concept of autonomous fire attack planning under dynamic killing network, and sums up the key technical points that need to be solved to realize the key points of unmanned autonomous fire control attack at present through the assumption of multi-target autonomous attack in air-ground situations.

Facing the dynamically changing battlefield environment, it has become a key solution to improve the survivability of UAV battlefield by completing the attack task in the shortest time. With the continuous improvement of computing power, it will be possible to transfer the attack solution from the ground to the UAV airborne platform. Efficient and reliable autonomous unmanned attack must be the future development trend.

References

1. Fusano, A., Sato, H., Namatame, A.: Multi-agent based combat simulation from OODA and network perspective. In: 2011 UK Sim 1st International Conference, pp. 249–254 (2011)
2. Blasch, E.P., Breton, R., Valin, P., et al.: User information fusion decision making analysis with the G-OODA model. In: Information Fusion, 2011 Proceedings of the 14th International Conference, pp. 1–8 (2011)
3. Cheater, J.C.: Accelerating the Kill Chain Via Future Unmanned Aircraft. Air University, Alabama (2007)
4. Marzolf, G.S.: Time-Critical Targeting Predictive Versus Reactionary Methods: An Analysis for the Future. Air University, Alabama (2004)
5. Chen, H.J.: Research on Combat Effectiveness Evaluation Method of UAV Formation Based on Bayesian Network. Nanjing University of Posts and Telecommunications, Nanjing (2020)
6. Du, Z.B., Chen, Y.D.: Review on testing and evaluation of UAV's autonomous operational ability. Aero Weaponry **28**(6), 58–65 (2021)

Adaptive Beamforming Method Based on Virtual Array

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Abstract. In order to solve the problem that traditional beamforming technology is limited by Rayleigh Limitation and does not have special suppression ability to the interference signal, an adaptive beamforming algorithm based on virtual array is proposed. Firstly, on the basis of conventional beamforming, the aperture of underwater acoustic array is expanded virtually by vector weighting of dynamic signal data of moving array, which improves beam quality; Then, the adaptive beamforming algorithm is used to calculate the weighting coefficient of each array element and automatically correct it with the change of environment, which solves the problem that traditional beamforming has no special ability to suppress the interference signal; Finally, the spatial smoothing technique is used to remove the coherence of signal and solve the problem of signal coherence. The performance of adaptive beamforming algorithm after virtual element and space smoothing is verified by Matlab simulation, which proves the superiority of the above method.

Keywords: Virtual array · Adaptive beamforming · Signal coherence · Spatial smoothing

1 Spatial Smoothing Technology

Conventional beamforming algorithm (CBF) is an improved algorithm to the earlier spatial filtering algorithm. In the beamforming process, conventional beamforming technology has some shortcomings: first, due to Rayleigh's limitation [1–5], in order to improve the resolution, the number of array elements or the spacing of array elements can only be when the wavelength and frequency are constant. However, increasing the number of array elements will increase the configuration and production cost of the detection system [6], which will encounter more resistance in the actual implementation, and the expansion of array spacing will also appear gate flag phenomenon, and the aperture size can be made is also limited. Secondly, traditional beamforming strengthens the signal by compensating the signal received in the target direction, but has no special ability to suppress the interference signal.

In order to solve the shortcomings of conventional beamforming, Friedlander from the University of Washington first proposed using virtual array technology to improve resolution in the early 1990s [7]. Ping-an Li of Northwestern Polytechnical University and Feng-gang Yan of Harbin Institute of Technology made further research. Ping-an

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Li extended UN-ESRIT algorithm by using virtual interpolation technology for array real array [8], and Feng-gang Yan adopted S-MUSIC algorithm for virtual array [9]. However, these methods decompose the covariance matrix in the array sampled signal, and some characteristics of the signal itself are damaged, which will also affect the subsequent processing of the array received signal. Later, Sanudin proposed an improved LP algorithm [10], which adopted the cost function in the calculation of spatial power to obtain the estimation of the direction of arrival with low deviation, thus improving the accuracy of the estimation of virtual array metadata. However, this algorithm cannot solve the problem of high reverberation interference in the case of low SNR.

As the traditional beamforming physical array is limited by Rayleigh limit and does not have special suppression ability to the interference signal [8], this paper proposes an adaptive beamforming algorithm based on virtual array element. In this algorithm, the dynamic signal data of moving array is weighted by vector, and the aperture of underwater acoustic array is expanded virtually. Then, the adaptive beamforming algorithm is used to calculate the weighted coefficients of each array element and automatically correct them with the change of environment. The spatial smoothing technique is used to solve the problem of signal coherence while overcoming the traditional beamforming's inability to suppress interference signals.

2 Algorithm Description

2.1 Covariance of Spatial Smoothing

The principle of space smoothing technology is to divide the uniform line array into several partially overlapping sub-arrays, calculate the covariance matrix of each sub-array respectively, and then make an equivalent covariance matrix to replace the original covariance matrix by arithmetic average. If the number of elements of the sub-array is $m \geq N$ (number of sources), When the number of subarrays is $p \geq N$, the covariance matrix after space smoothing can be guaranteed to recover non-singularity. It removes the coherence of the signal. The spatial smoothing technology can be divided into two steps: forward spatial smoothing and backward spatial smoothing.

Forward Space Smoothing. The principle of forward space smoothing is shown in Fig. 1. The uniform linear array with the element number of M is divided into overlapping p sub-arrays. The element number of each word array is m, Among them $p = M - m + 1$.

Take the first subarray on the left as the reference subarray, then smooth each subarray before and after is $x_1^f, x_2^f, \cdots x_p^f$, The respective data vectors.

$$\begin{cases} x_1^f = [x_1, x_2, \cdots x_m] \\ x_2^f = [x_2, x_3, \cdots x_{m+1}] \\ \vdots \\ x_p^f = [x_p, x_{p+1}, \cdots x_M] \end{cases} \tag{1}$$

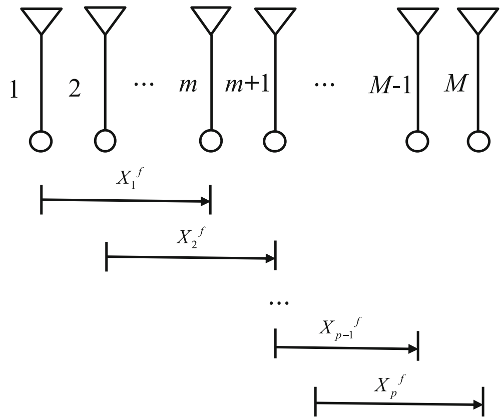

Fig. 1. Schematic diagram of forward space smoothing

The forward smoothing covariance matrix of each subarray is summed and the forward smoothing covariance matrix is R^f:

$$R^f = \frac{1}{p}\sum_{i=1}^{p} R_i^f = \frac{1}{M-m+1}\sum_{i=1}^{p} R_i^f \tag{2}$$

The $R_i^f = E[x_i^f (x_i^f)^H]$ shows that the dimension of the covariance matrix obtained by forward smoothing decreases, and the loss of freedom limits the ability of the adaptive beamforming algorithm to interference and noise to a certain extent.

Smooth Forward and Backward Space. Backward smoothing is also needed on the basis of forward smoothing, as shown in the following Fig. 2.

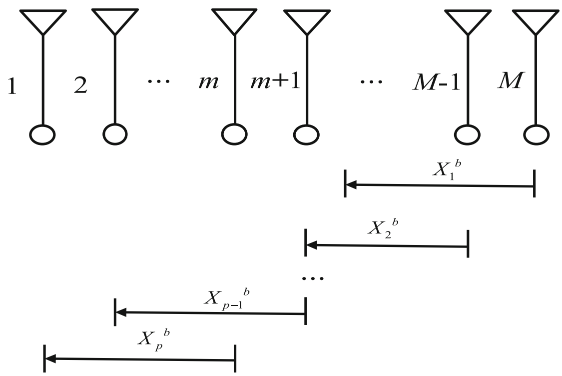

Fig. 2. Backward smoothing diagram

Similarly, after smoothing each sub-array is $x_1^b, x_2^b, \cdots x_p^b$.The respective data vectors are:

$$\begin{cases} x_1^b = [x_M, x_{M-1}, \cdots x_{M-m+1}] \\ x_2^b = [x_{M-1}, x_{M-2}, \cdots x_{M-m}] \\ \vdots \\ x_p^b = [x_m, x_{m-1}, \cdots x_1] \end{cases} \tag{3}$$

The forward smoothing covariance matrix B is obtained by summing the covariance matrix of each subarray of backward smoothing is R^b:

$$R^b = \frac{1}{p}\sum_{i=1}^{p} R_i^b = \frac{1}{M-m+1}\sum_{i=1}^{p} R_i^b \tag{4}$$

Among them:

$$R_i^b = E[x_i^b (x_i^b)^H] \tag{5}$$

Finally, the covariance matrix processed by smoothing technology is expressed as:

$$R_{fb} = \frac{R^f + R^b}{2} \tag{6}$$

2.2 Adaptive Beamforming

According to Sect. 2.1, the subcovariance matrix of spatial smoothness is contained in R_x, it can be known from the number of subarrays p and the number of elements of subarrays m,The forward sliding q submatrix covariance R_q^f is equal to the m order submatrix from the q row to the $q+m-1$ column in R_x, and the backward smoothing is essentially the conjugate inversion of the forward smoothing data.

Therefore it can be concluded that:

$$R_{p-q+1}^b = J(R_q^f)^* J \tag{7}$$

Among them:

$$J = \begin{bmatrix} 0 & \cdots & 0 & 1 \\ 0 & \cdots & 1 & 0 \\ \vdots & \iddots & \vdots & \vdots \\ 1 & \cdots & 0 & 0 \end{bmatrix} \tag{8}$$

Each subarray receives data and then smooth forward and backward. Under the L sampling, the sampling covariance matrix of received signal $x(k)$ is:

$$\hat{R}_x = \frac{1}{L}\sum_{K=1}^{L} x(k)x^H(k) \tag{9}$$

According to the forward and backward smoothing, the covariance matrix after processing can be obtained:

$$R^{fb} = \frac{1}{2p}\sum_{q=1}^{p}[R_q^f + J(R_q^f)^* J] \tag{10}$$

Set the guidance vector of the desired signal $a(\theta)$, and substitute R^{fb} into the adaptive beamforming algorithm, and obtain the optimal weight vector of the adaptive beamforming algorithm based on spatial smoothing technology:

$$\omega_{FBMV} = \frac{R_{fb}^{-1}a(\theta)}{a(\theta)^H R_{fb}^{-1}a(\theta)} \tag{11}$$

The output of ω_{FBMV} substituted into the beamformers is:

$$y(k) = \frac{1}{p}\sum \omega_{FBMV}^H X_q(k) \tag{12}$$

2.3 Beam Output Under Virtual Aperture

The principle of the virtual array method is as follows: By transmitting and receiving dynamic data at different angles at different times during ship sailing, the spatial and temporal sampling conversion is realized, and then the spatial multi-fast shot echo data is fused to realize array aperture expansion. Then, according to the output of sub-array beamforming obtained in Sect. 2.2, the output of adaptive beamforming based on spatial smoothing technology is finally obtained under virtual aperture:

$$Y(k) = \frac{1}{M_0 - M_1 + 1}\sum_{i=1}^{M_0 - M_1 + 1} y_i(k) \tag{13}$$

3 Simulation Analysis

In order to verify the effectiveness of adaptive beamforming based on virtual array, the simulation is considered from two aspects: first, to verify the improvement of adaptive beamforming algorithm under virtual array aperture; the second is to verify the improvement of adaptive beamforming algorithm with spatial smoothing.

3.1 Influence of Virtual Array on Algorithm Performance

In order to verify the improvement of beamforming algorithm by virtual array, the following simulation is designed (Table 1).

Table 1. Simulation parameter setting 1.

	Desired signal	Interference signal1	Interference signal2
Incidence Angle/°	0	−30	30
SF/kHz	115	100	75
SNR/dB	10	20	20

When both the expected signal and the interference signal are irrelevant, the specific parameters are shown in Table 1. Under the above conditions, the beamforming algorithm after adaptive beamforming and virtual array element is processed respectively in Matlab, and the power spectrum and array direction diagrams are generated, as shown in Figs. 3 and 4.

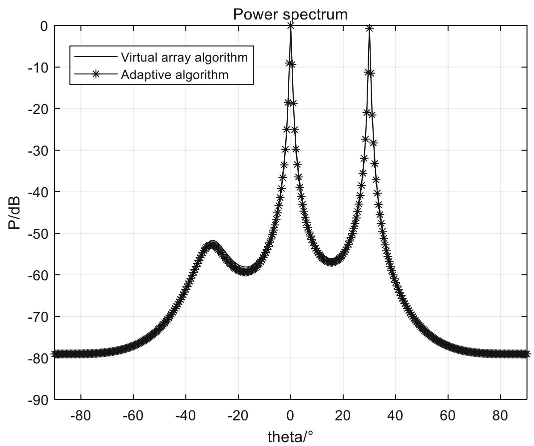

Fig. 3. Power spectrum comparison between the adaptive algorithm and the virtual matrix algorithm

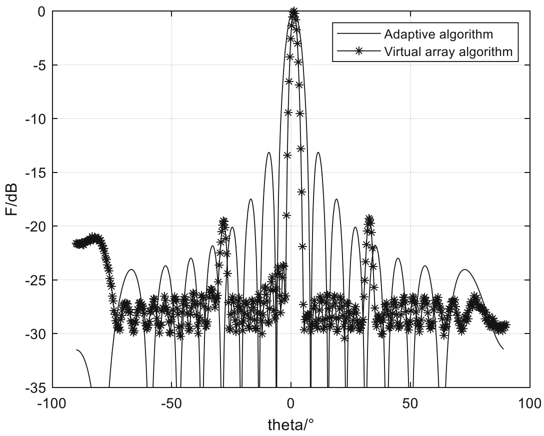

Fig. 4. Direction diagram of adaptive algorithm and virtual matrix algorithm

As can be seen from Fig. 3, when the expected signal is irrelevant to both the two interference signals, the adaptive beamforming before and after the virtual array can distinguish the azimuth of the two signal sources in the scanning area. By moving the expanded array aperture through the hydrophone, the three signal sources do not change the array direction, so it is expected that the power of the two algorithms does not change.

As can be seen from Fig. 4, when the desired signal and interference signal two mutually to the works, the adaptive beamforming algorithm in the virtual array can do before and after the yuan increased expectation direction signal, and the direction of the 30° and 60° zero trap formation, but the increase of virtual array aperture after yuan winner lobe width decreased greatly and the side lobe were also obvious inhibition.

3.2 Influence of Spatial Smoothing Technology on Algorithm Performance

When other conditions remain unchanged, the setting parameters are shown in Table 2. The expected signal and interfering signal 1 are set at the same frequency, that is, the expected signal is only coherent with interfering signal 1 but irrelevant with interfering signal 2.

Table 2. Simulation parameter Settings.

	Desired signal	Interference signal1	Interference signal2
Incidence angle/°	0	−30	30
SF/kHz	115	115	75
SNR/dB	10	10	20

In the same way, Matlab is used to compare the power spectrum and array pattern before and after adaptive beamforming in space smoothing technology. See Figs. 5 and 6.

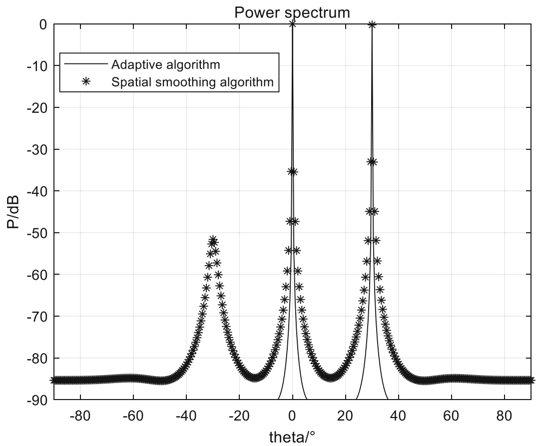

Fig. 5. Power spectrum comparison between adaptive algorithm and spatial smoothing algorithm

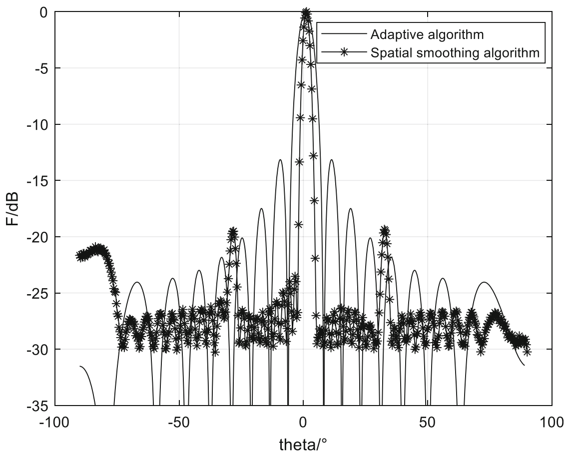

Fig. 6. Direction diagram of adaptive algorithm and spatial smoothing algorithm

When the expected signal is set to be coherent with the interference signal 1, it is obvious from the power spectrum that the adaptive beamforming algorithm after the spatial smoothing technology can identify three signals, while the adaptive beamforming algorithm can only identify two irrelevant signals, which reflects the coherence of the spatial smoothing technology. However, adaptive beamforming after space smoothing sacrifices part of array aperture, so the peak is not as sharp as adaptive beamforming itself.

Can be seen from the Fig. 6, where there is no coherent join space smooth solution, the sidelobe peak is higher, and after the spatial smoothing technology involved in the direction of the adaptive beamforming figure in suppress coherent signal main lobe of the beam at the same time also has significantly narrowed, while the spatial smoothing technique can sacrifice part of the aperture, but the virtual array yuan also expanded the part of the array, The beam is greatly optimized.

4 Conclusion

In this paper, based on conventional beamforming, the aperture of underwater acoustic array is expanded virtually by vector weighting of dynamic signal data of moving array. Then, the adaptive beamforming algorithm is used to calculate the weighted coefficient of each array element and automatically correct it with the change of environment, which overcomes the problem that the traditional beamforming has no special suppression ability to the interference signal. Finally, the spatial smoothing technology is used to remove the coherence of signal and solve the problem of signal coherence.

References

1. Wang, M.Y., Zhu, W.: Beamforming of virtual arrays with non-equidistance vector arrays. Journal **36**(4), 42–45 (2012)
2. Zhang, W.M., Guo, H.T., Jin, S.S., et al.: Acoustic technology. Journal **39**(2), 134–140 (2020)
3. Yang, Y.: Blind Separation of Acoustic Scattering Signals from Underwater Targets. Harbin Engineering University, Harbin (2017)
4. Solomon, I.S., Knight, A.J.: Special processing of signals received by platform mounted sonar. Journal **27**(1), 57–65 (2002)
5. Wang, Z.: Research on Beam Scanning Technology of Millimeter Wave Large-Scale Array Antenna. Hangzhou Dianzi University (2019)
6. Hu, P., Yang, Y.X., Yang, S.E.: Acoustic technology. Journal **26**(4), 714–717 (2007)
7. Li, Q.H.: The Theory of Sonar Signal Processing (Second Edition). Haiyang Publishing House, Beijing (2000)
8. Xu, M., Yang, Y., Xu, L., et al.: Space virtual array beamforming technology based on compressed sensing. Journal **18**(2), 47–54 (2020)
9. Pan, F.: Research on Virtual Expansion and Beamforming of Array Antenna. Tianjin University of Technology (2019)
10. Sanudin, R., Erdogan, A.T., Arslan, T.: Modified linear prediction algorithm with low bias estimator. In: International Conference on Radar Systems (IET) (2013)

Adaptive Unscented Kalman Filter Algorithm for Multi-domain Command and Control Information Transmission

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Abstract. This paper studies the carrier frequency tracking algorithm of multi-domain command and control transmission signal in low Carrier-Noise-Ratio (CNR) and high dynamic conditions. On the basis of analyzing the shortcomings of existing methods, a closed loop carrier frequency tracking algorithm of simplified adaptive unscented Kalman filter (AUKF) is presented. This new algorithm can not only avoid the errors due to linearization because of its good nonlinear processing capability, but also can eliminate the phase information of the phase shift keying (PSK) modulation. In addition, it is found that the new algorithm could estimate the measurement noise covariance and process noise covariance adaptively, so it is able to compensate the errors resulting from the change of the noise statistics. The simulations show that the simplified AUKF algorithm has a much smaller frequency estimation error than that of the UKF algorithm while keeping the convergence speed. Furthermore, the simplified AUKF algorithm has a lower computation complexity than the original AUKF algorithm. So it will have great significance on the information transmission of multi-domain command and control.

Keywords: Multi-domain command and control · Frequency estimation · Adaptive algorithms · Estimation error · Computational complexity

1 Introduction

It is necessary to continuously enrich and improve the construction of information support environment for joint command and control, so as to ensure the smooth command and control information transmission of geographically dispersed heterogeneous platforms. Then, the whole region and all-time connectivity across land, sea, air and space will be realized. Due to the wide location distribution of multi-domain platforms, long communication distance and fast relative motion speed between different task platforms, the received signals have the characteristics of extremely low Carrier-Noise-Ratio (CNR) and high Doppler dynamics, which brings difficulties to the reception and detection of signals. In the process of signal receiving and detection, carrier frequency tracking is one of the most important segments, which usually adopts frequency locking or phase-locked loop [1, 2]. Because of the extremely low CNR, the bandwidth of the frequency locking or phase-locked loop must be designed very

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narrow to keep the loop sensitivity and frequency tracking accuracy. Accordingly the capture range should be relatively narrow. However, for the high dynamic signals, Doppler shift may be larger than the loop tracking bandwidth, so the tracking of the high dynamic signals will not be assurances.

To resolve the problem, some targeted algorithms are developed, mainly including maximum likelihood estimation (MLE) [3], cross-product automatic frequency control (CPAFC) loop, extended Kalman filter (EKF) [4], unscented Kalman filter (UKF) [5, 6], overlapping discrete Fourier transform-based automatic frequency control (ODAFC) and so on. The MLE algorithm estimates the frequency based on a certain observational data, whose computation amount is too large to realize. The CPAFC and ODAFC algorithms are significantly limited by the tracking bandwidth and are difficult to solve the contradiction between high dynamic and low carrier noise ratio. The EKF algorithm linearizes the nonlinear observation equation [4]. So it will introduce a large error and reduce the stability and tracking accuracy.

UKF algorithm can directly use nonlinear model without introducing linearization error, so the stability and tracking accuracy will be improved [7–9]. But the CNR threshold of conventional UKF algorithm is still high, which is difficult to meet the requirements of multi-domain signals reception and detection. So a simplified adaptive unscented Kalman filter (AUKF) based on closed loop structure is proposed in this paper, which uses the nonlinear processing ability of the AUKF. Taking the result of the cross product operation of the signal as the observation variable of AUKF, the cross product phase and frequency variation are estimated. For this new algorithm, the phase information is removed in the estimated state vector, so a larger capture range and low CNR threshold will be obtained. Furthermore, the algorithm can estimate and adjust the noise variance matrix adaptively to improve tracking accuracy, and has the advantage of low computational complexity. The simulation results also prove that the new algorithm is effective in improving the signal frequency tracking performance under the condition of low CNR and high dynamic, and is of great significance for the signal detection of multi-domain command and control.

2 Carrier Tracking Loop

The closed loop AUKF is used in this paper. The algorithm of removing phase information can obtain lower CNR threshold compared with the algorithm of estimating phase. Therefore, the phase information needs to be removed before AUKF filter.

The phase information is removed by cross product operation, and then a closed loop carrier tracking algorithm of AUKF assisted by second-order loop filter is adopted. The loop structure of the algorithm is given in Fig. 1.