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Study on the Jamming-Position Maneuver Algorithm of Off-Board Active Electronic Countermeasure Unmanned Surface Vehicles

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ABSTRACT The existing off-board active decoys face such common technical problems as short action time, limited jamming power, and difficult control over deployment situation and effective directive jamming beam direction. For this reason, this paper introduces a new mode and process of anti-missile combat, which places the radar active decoy on an unmanned surface vehicle (USV) to collaborate with the surface warship during the off-board active anti-missile combat. Following the principles of radar terminal guidance centroid jamming, a real-time calculation method for the effective area of off-board active jamming is developed, and the jamming position maneuver strategy under the collaboration of the USV and the surface warship is proposed to implement the off-board active anti-missile combat. The proposed strategy satisfies the needs of long-time, high-power, stable, and effective off-board jamming against incoming anti-ship missiles. This paper further verifies the effectiveness of the proposed strategy in the simulated and live firing confrontations.

INDEX TERMS Electronic countermeasures unmanned surface vehicle (ECM USV), off-board active decoy, centroid jamming, jamming-position maneuver.

I. INTRODUCTION

In modern sea warfare, the biggest threat of surface warships is lot kinds of multi-directions, multi-waves and high-density anti-ship missiles. The important mission of surface warship defense is to effectively confront with the incoming anti-ship missiles [1], [2].

At present, surface warships rely mainly on some soft-kill and hard-kill weapons such as ship-to-air missile, short-range small-caliber naval gun, and ship-borne electronic countermeasure (ECM) system for integrated anti-missile combat. Among these weapons, active jamming is one of the common ECMs to protect warships against radar terminal guidance anti-ship missiles. By receiving, modulating and forwarding the radio-frequency signal of the radar seeker on the incoming missiles, active jamming could create a great number of false targets with large radar cross section (RCS) on the sea to achieve the goal of anti-missile defense [3]–[5].

Based on different installation and action positions, active jamming is classified into on-board and off-board. In the on-board active jamming, the jammer on a warship actively transmits the radio-frequency signal for jamming, which may easily make the warship a target of active tracking and guidance missiles. Moreover, on-board active jamming has some practical problems such as difficult management of warship electromagnetic compatibility and dramatic reduction of effective combat time, so that it is dangerous or not suitable to apply in some cases [6]–[9].

In developed countries, the navy is therefore focusing on the development of off-board radar active decoy technology. By moving the jamming source from on-board to off-board, the technology could create simulated false targets to effectively provide cover for the warship against the seeker with clutter tracking and narrow-gate tracking ability [10]–[13].

The main contribution of this paper can be stated as follows: first, based on the advantages and disadvantages of the existing off-board active jamming measures, a new mode of anti-missile combat by implementing the off-board active jamming through unmanned surface vessels (USVs) is proposed; secondly, the jamming-position maneuver strategy in the proposed mode is studied through theoretical analysis and simulation, which realizes the automatic calculation of jamming-position area and provides the input for decision-making on the autonomous anti-missile confrontation

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maneuver of USVs, last, the effectiveness of the proposed mode and strategy in the anti-missile defense is verified through live firing confrontations.

II. GUIDELINES CHARACTERISTICS OF THE EXISTING OFF-BOARD ACTIVE RADAR DECOYS

Based on their carrying mode and application method, the existing off-board active radar decoys could be categorized into parachuted type, suspended type, and floated type and so on, e.g. ''Nulka'' suspended missile active radar decoy (jointly developed by the United States and Australia), ''Siren'' parachuted off-board decoy (Britain), and ''TOAD'' towed active radar decoy (Britain), as shown in Figure 1.

FIGURE 1. Typical off-board active radar decoys developed by other countries.

Off-board active decoys could be utilized to achieve the effective jamming against radar terminal guidance anti-ship missiles under the basic conditions as follows [14]–[16]:

(1) The beam angle of a working off-board active decoy should be able to dead against the attack direction of the anti-ship missile, so that it is ensured that the radio-frequency signal from the radar seeker of the anti-ship missile is received and the jamming signal is transmitted towards it;

(2) The jamming signal transmitted by the off-board active decoy must have sufficient jamming power;

(3) The off-board active decoy must implement the continuous and stable jamming against the incoming anti-ship missile;

(4) Based on the direction of the incoming anti-ship missile, the off-board active decoy should adjust its orientation with the surface warship under its protection, that is, adjusting the off-board active combat formation.

However, the existing decoys presented in Figure 1, including parachuted, suspended, and floated off-board active decoys, have the following limitations:

(1) A parachuted off-board active decoy is launched from the warship. It is carried by a parachute and descends slowly to implement the jamming against the incoming missile. The decoy is normally small and equipped with finite battery energy, so that its jamming power is limited. Moreover, the decoy rotates during the descent, making it difficult to maintain the continuous and stable jamming in the direction of the incoming missile. Besides, the descent lasts for a short time, so that effective jamming is often over in only one or several minutes;

(2) A suspended active decoy, which is similar to a small aircraft, could implement the jamming against the incoming missile by means of the active jammer it carries. The suspended active decoy could make use of its flight control mechanism to maintain the dynamic jamming formation with the warship, and could also rotate to adjust the jamming direction. Therefore, it could maintain the stable jamming against the incoming missile. Like parachuted off-board active decoys, suspended active decoys have similar problems such as small battery, limited jamming power, short action distance, high vulnerability to sea wind, and difficult control, because of its limited carrying capacity;

(3) A towed active decoy on the sea is towed by a warship using a cable during the confrontation. A towing platform is relatively large, and has sufficient battery, so that it could meet the needs of high jamming power. Nevertheless, the towed active decoy could only maintain the single mode of stern towed jamming, and implement the jamming against the incoming missiles only in a specific direction, which causes the blind zone of jamming at the bow of the warship. In addition, its long cable (normally several hundred meters) seriously restricts the maneuvering performance of the warship, making this kind of decoy more inconvenient on application.

In general, the existing off-board active decoys may overcome the shortcomings of on-board active jamming to some extent, but still have such limitations as short action time, limited jamming power, and towing restriction for warship maneuver. Moreover, there are some common technical problems including difficult control over deployment situation and effective directive jamming beam direction, so that they could not maintain the continuous, stable and high-power jamming against the incoming missiles for a long time, which undermines the effect of off-board active jamming in combats.

III. COMBAT MODE OF OFF-BOARD ACTIVE ELECTRONIC COUNTERMEASURE UNMANNED SURFACE VEHICLES

As revealed in the previous analysis, the existing off-board active radar decoys have some limitations, but they could complement each other. Therefore, their advantages could be combined in the optimized design to improve the performance of off-board active anti-missile defense.

Suspended active decoys could be deployed flexibly and easily made into the desired defense formation, but subject to limited jamming power and short active time. Towed active decoys feature high jamming power and long work time, but have a fixed defense formation. For this reason, this paper puts forward the concept of ''off-board active electronic countermeasure unmanned surface vehicle (ECM USV)'', which realizes the collaborative navigation and tactical cooperation between the USV and the surface warship with taking the USV as the maneuvering platform and utilizing the autonomous navigation technology. The USV is equipped with active radar decoy to electronically support the off-board active anti-missile combat of the surface warship, and enhance the integrated anti-missile combat ability of the surface warship formation by means of combat decision-making and remote command & control.

Off-board active ECM USV could effectively overcome the shortcomings of the existing off-board active decoys including difficult control over jamming beam, short stay in the air, and low jamming power. Moreover, it offers jamming with such combined advantages as flexible situation establishment, small blind zone, long active time, no increase of warship radiation, and no effect on warship maneuvering. This new off-board active anti-missile combat mode could improve the anti-missile defense capability of surface warship formation Figure 2 presents an off-board active ECM USV.

FIGURE 2. Off-board active ECM USV.

The process of applying this USV in combats is as follows:

(1) Accompanying and escorting. The surface warship could inform the USV of its location, course, speed and other motion information through the communication system. Based on its own current location, the USV could utilize the autonomous navigation technology and implement the automatic control over the speed (throttle) and course (rudder angle) to automatically track and accompany the surface warship at a certain distance from and a relative bearing with the surface warship. In this way, the USV realizes the escort formation with the surface warship.

(2) Air-defense warning. During the navigation of the surface warship, a ship-borne air-defense warning radar is utilized to check and detect the airspace in the combat zone. Warning is triggered in a timely manner when any threat of anti-ship missile is detected.

(3) Assessing threat. Based on the position and motion of the detected incoming anti-ship missile(s), the warship command and control system assesses the threat of such anti-ship missile(s), and then determines target and sequence of the anti-missile defense.

(4) Assigning missions. Based on the battlefield situation and the distribution of ECM USVs (formation), the warship command and control system assigns the mission of off-board active anti-missile support to a USV, transmits the anti-missile combat command and target indication information of the incoming missile(s) to the USV.

(5) Jamming-position maneuver. Based on the information on the position and motion of the incoming anti-ship missile(s) received from the warship, the ECM USV to which the mission of anti-missile defense is assigned calculates and determines the effective position to perform the off-board active jamming mission in a real-time manner (see Section V). With the function of autonomous navigation, the USV could realize fast maneuvering to take the jamming position and form the defense.

(6) Implementing jamming. The USV controls the off-board active decoy it carries to start and implement the jamming against the incoming anti-ship missile(s). By turning the bow of the USV or controlling the bearing servo of the decoy, the decoy jamming beam direction is turned towards the incoming missile(s) to implement the stable and aimed jamming against them.

(7) Evaluating effectiveness. During the confrontation, the effect of off-board active anti-missile defense is evaluated in a real-time manner by integrating the information received by the active decoy including radar seeker radio-frequency, anti-ship missile flight path change, and varying degree of threat.

The schematic diagram of off-board active anti-missile confrontation is presented in Figure 3.

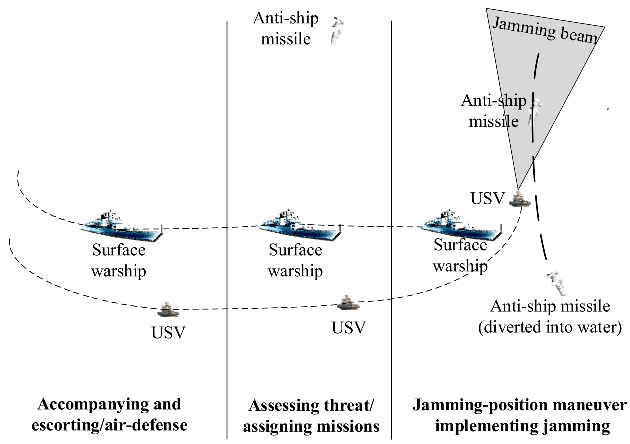

FIGURE 3. Off-board active ECM USV.

IV. ELECTRONIC COUNTERMEASURE UNMANNED SURFACE VEHICLE OFF-BOARD ACTIVE CENTROID JAMMING MODEL

The selection of jamming position is crucial and directly affects the effectiveness of anti-missile defense when a USV executes the mission of off-board active anti-missile combat. Based on the relative dynamic position of anti-ship missile and surface warship, real-time calculation must be conducted to choose the jamming position reasonably following the working principles and using the performance indicators of active decoy.

At present, off-board active decoys often provide the centroid jamming against the anti-ship missiles during the phase of radar terminal guidance [16]–[24]. The echo of the active decoy on the USV and the false targets it creates falls into the same beam and resolution cell as the echo of the warship. When an anti-ship missile approaches a surface warship, the seeker of the anti-ship missile is unable to identify the jamming echo signal of the active decoy from the echo signal of the surface warship. The beam center of the seeker will point at the energy center of target echo and jamming signal, so as to realize the centroid jamming. When the missile approaches the surface warship target and the active jamming decoy, if the jamming echo is stronger than the target echo, the missile's tracking gate will gradually deviate from the target warship, but track the echo of the false targets created by the active decoy. In this way, the missile is diverted by the decoy. The process of the ECM USV diverting the radar seeker of anti-ship missile through off-board active centroid jamming is shown in Figure 4.

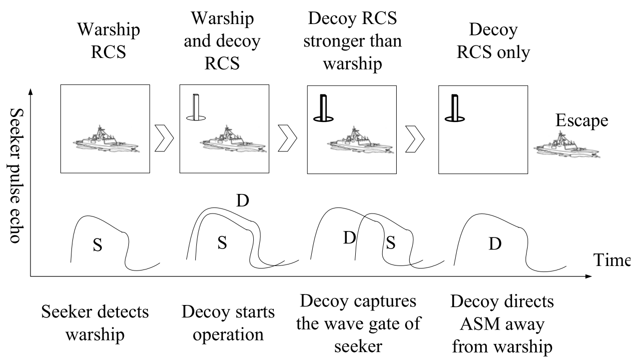

FIGURE 4. Off-board active jamming process of ECM USV.

Obviously, if an active jamming decoy is utilized for centroid jamming, the jamming echo must be in the same resolution cell as the surface warship echo, and the signals of the jamming echo must be stronger than the surface warship echo. In other words, there are higher requirements for the jamming position selection of the active jamming decoy and the platform strategy of the USV.

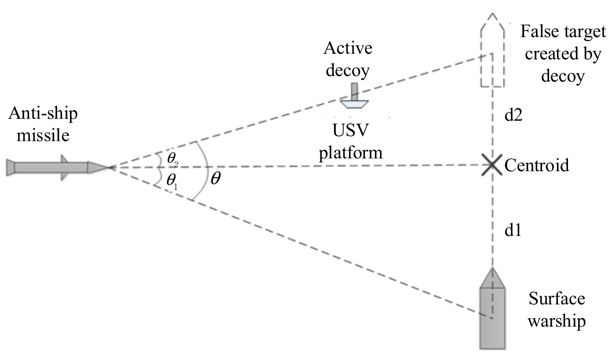

FIGURE 5. USV off-board active centroid jamming for diverting missiles.

The schematic diagram of off-board active centroid jamming is presented in Figure 5. The opening angle of the active decoy with the surface warship against the anti-ship missile terminal guidance radar is θ. The opening angle of the centroid with the surface warship against the terminal guidance radar is θ_1. The opening angle of the centroid with the active decoy target against the anti-ship missile radar is θ_2. The radar reflection cross section of the surface warship is σ_1. The energy of wave reflected by radar is P_1. The active decoy transmitting power is P_2, equivalent to the reflected energy of the target with the cross section σ_2.

According to the centroid principles, there is:

$$\theta_1 = \frac{\sigma_1}{\sigma_1 + \sigma_2}\theta = \frac{P_1}{P_1 + P_2}\theta \tag{1}$$

$$\theta_2 = \frac{\sigma_2}{\sigma_1 + \sigma_2}\theta = \frac{P_2}{P_1 + P_2}\theta \tag{2}$$

The horizontal distance from the centroid to the surface warship and the decoy in the direction vertical to the missile tracking axis is d_1 and d_2 respectively, so that:

$$\frac{d_1}{d_2} = \frac{tg\theta_1}{tg\theta_2} \tag{3}$$

The jamming blanket factor K_j is defined as the ratio of the active decoy radar jamming signal power P_2 and the radar wave energy reflected on the radar cross section of the surface warship P_1, that is:

$$K_j = \frac{P_2}{P_1} = \frac{\sigma_2}{\sigma_1}, \tag{4}$$

As revealed, if $K_j > 1$, the energy of the jamming signal transmitted by the active decoy is greater than that of the echo signal from the surface warship, so that the anti-ship missile will be diverted towards the active decoy; if $K_j < 1$, the anti-ship missile will be attracted towards the surface warship.

V. JAMMING-POSITION MANEUVER STRATEGY FOR OFF-BOARD ACTIVE ELECTRONIC COUNTERMEASURE UNMANNED SURFACE VEHICLES

Based on the off-board active centroid jamming model of electronic countermeasure unmanned surface vehicle (ECM USV), the decoy must be deployed under the following conditions to achieve the good effect of centroid decoying.

Condition 1: Before the anti-ship missile reaches the critical angle, the false target created by the active decoy and the surface warship should fall into the seeker beam coverage of the anti-ship missile. Moreover, the false target should be in the same range resolution cell of the seeker as the surface warship, so that the terminal guidance radar of the anti-ship missile could not identify the echo of the surface warship target from the echo of the false target based on their direction and distance. In this case, the anti-ship missile will have to track the echo centroid.

Condition 2: The active jamming decoy could easily realize the distance deception, since most of the false targets it creates are on the line between the anti-ship missile and the active decoy. However, it is more complicated and difficult to achieve the angle deception. For this reason, the active decoy jamming position must be determined to make the active decoy, the surface warship, and the anti-ship missile form a triangle, and prevent them from falling onto the same line. Therefore, the echo centroid could be as far away from the surface warship as possible in the direction vertical to the missile tracking axis (i.e. the value of d_1 in Figure 5 is as large as possible), so as to achieve the effect of centroid decoying as expected.

Condition 3: When the anti-ship missile reaches the critical angle, the active decoy jamming position must ensure that the jamming blanket factor K_j is greater than 1, so as to divert the tracking wave gate of the anti-ship missile towards the false target.

Condition 4: The jamming position of the active jamming decoy must be between the warship and the anti-ship missile, to against such anti-jamming countermeasures as front tracking and frequency agility of the anti-ship missile.

The geometrical locations of the active decoy, the protected surface warship, and the anti-ship missile are presented in Figure 6. Considering the above four conditions, the deployment interval of the off-board active radar decoy for effective centroid jamming is analyzed in the subsequent section.

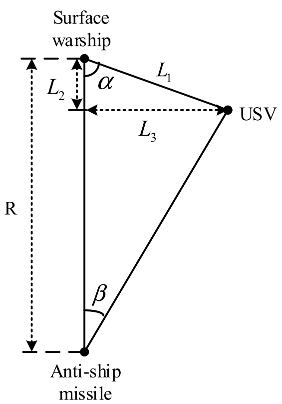

FIGURE 6. Geometrical locations of active decoy, surface warship, and anti-ship missile.

The geometrical locations of the active decoy, the protected surface warship, and the anti-ship missile are presented in Figure 6. Considering the above four conditions, the deployment interval of the off-board active radar decoy for effective centroid jamming is analyzed in the subsequent section.

A. FEASIBLE INTERVAL UNDER CONDITION 1

At the beginning of the centroid jamming, the radar seeker of the anti-ship missile may track the warship target stably, so that the antenna beam is directed at the echo reflection center of the warship. Condition 1 requires that the echoes from the false target generated by the active decoy and the actual target fall into the same range and bearing resolution cell [11]. By setting different modulation and forwarding delays dynamically [12], the active decoy could generate a number of densely and continuously arranged false targets along the line linked to the missile, making it easy to meet such requirement.

In terms of direction, the false targets generated could be considered approximately arranged in the direction of the line connecting the active decoy with the missile. Therefore, to guarantee that the false targets and the surface warship fall into the seeker beam coverage of the anti-ship missile, the active decoy and the surface warship must be kept in the radar seeker beam coverage.

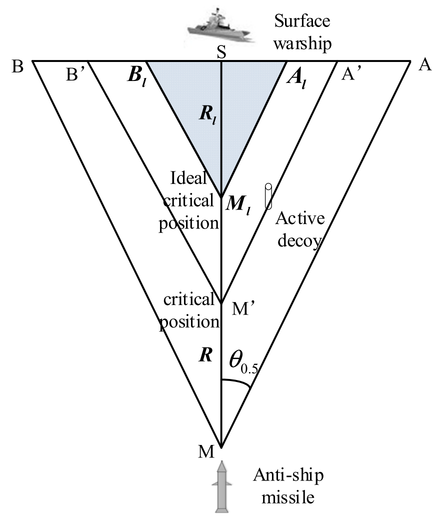

FIGURE 7. Effective deployment area of off-board active decoy under condition 1.

When the 3dB beam width of the radar seeker of the anti-ship missile is $\pm\theta_{0.5}$, the seeker beam has the coverage with the missile-target line as its center axis and the opening angle $\pm\theta_{0.5}$.To satisfy Condition 1, the active decoy should be located in the area ΔAMB as shown in Figure 7. Obviously, the coverage of the seeker beam decreases with the reduction of the missile-target distance. When the anti-ship missile flies from the point M to the point M', the coverage of the seeker beam shrinks from ΔAMB to ΔA'M'B'. When the anti-ship missile approaches the surface warship, if the active decoy is at the edge of the seeker beam coverage ΔA'M'B', the location of the anti-ship missile is the "critical" position [13], as shown in Figure 7. After passing the "critical" position, the surface warship and the active decoy will not be covered by the seeker beam of the anti-ship missile at the same time. If the anti-ship missile has a long distance from the surface warship after reaching the "critical" position, the active decoy could achieve a large jamming-to-signal ratio with a small transmission power at this time [14], so as to achieve the centroid decoying of the anti-ship missile. After being decoyed, the anti-ship missile may search again, recapture, and track the surface warship target. To achieve the effective centroid decoying, the missile-target distance at the critical position should not be very large. The maximum missile-target distance R_l at the critical position should be reasonably selected considering the capturing and maneuvering overload capacity of the incoming anti-ship missile. After determining the value of R_l, the area with the missile-target line as the center axis and the opening angle $\pm\theta_{0.5}$ will be the feasible deployment area that satisfies Condition 1. It is the shaded area $\Delta A_l M_l B_l$ in Figure 7.

B. FEASIBLE INTERVAL UNDER CONDITION 2

The active jamming decoy could easily realize the distance deception, but it is difficult to achieve the angle deception. In the jamming-position area $\Delta A_l M_l B_l$ that satisfies

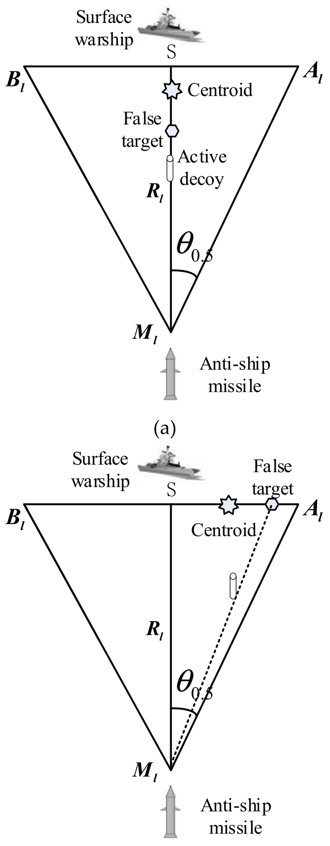

FIGURE 8. **Effective deployment area of off-board active decoy under condition 1. (a) Straight line;(b) Triangle.**

Condition 1, if the active decoy, the surface warship, and the anti-ship missile are on the same line, the active decoy could implement the distance deception jamming against the anti-ship missile, but the echo centroid is still on the missile-target line, and the missile is not kept away in terms of angle. In this case, the anti-ship missile may still fly in the direction of the surface warship, so that the surface warship faces a high risk of being hit by the missile, as shown in Figure 8(a). Therefore, a triangle should be created by the active decoy with the surface warship and the anti-ship missile to widen the angle between the echo centroid and the missile-target line, in order to achieve the effect of centroid decoying by conducting the angle deception over the anti-ship missile, as shown in Figure 8(b).

To effectively divert the echo centroid away from the missile-target line and achieve the good effect of angle deception, the active decoy should keep the horizontal distance from the surface warship (L_3 in Figure 6) more than M meters when the anti-ship missile passes the ''critical'' position. The value of M could be determined considering the length of the surface warship, the speed of the anti-ship missile, and other factors, and it is normally from one hundred meters to several hundred meters. In this way, the anti-ship missile has sufficient time to track the echo of the false targets after passing the ''critical position'', so that its flight path is diverted.

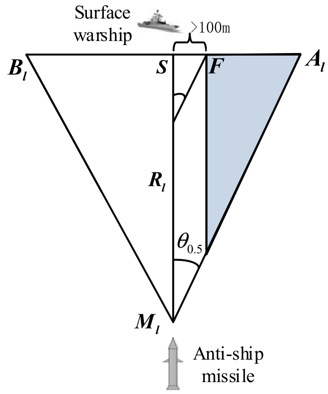

FIGURE 9. **Effective deployment area of off-board active decoy under conditions 1 and 2.**

Therefore, the interval of the active decoy jamming position that satisfies Condition 1 and Condition 2 simultaneously is determined, and it is the shaded area in Figure 9.

C. FEASIBLE INTERVAL UNDER CONDITION 3

According to Condition 3, when the anti-ship missile reaches the ''critical'' position, the active decoy jamming position must ensure that the jamming blanket factor K_j is greater than 1. Based on the geometry in Figure 6, the following equation is obtained:

$$\frac{L_1}{\sin\beta} = \frac{R}{\sin(180^\circ - \alpha - \beta)} \tag{5}$$

where R is the distance between the anti-ship missile and the surface warship, i.e. missile-warship distance; L_1 is the absolute distance between the surface warship and the active decoy; β is the angle formed by the line linking the anti-ship missile to the surface warship and the line connecting the anti-ship missile with the active decoy, i.e., warship-missile-decoy angle; α is the angle formed by the line linking the surface warship to the anti-ship missile and the line connecting the surface warship with the active decoy, i.e. missile-warship-decoy angle.

When the anti-ship missile reaches the ''critical'' position, β in Equation (5) is the 3dB beam width of the terminal guidance radar seeker of the anti-ship missile $\theta_{0.5}$, and the missile-target distance R is the missile-target distance at the ''critical'' position. The whole situation is shown in Figure 10.

To meet the requirements for the jamming blanket factor of the anti-ship missile K_j at the critical position, the active jamming decoy needs the equivalent radiated power P_jG_j that satisfies the following equation [15]:

$$P_jG_j = \frac{K_jP_tG_t\gamma\sigma \sin^2\alpha \sin^2\theta_{0.5}}{4\pi L_1^2 \sin^4(\alpha + \theta_{0.5})}, \tag{6}$$

where P_t is the peak power of the transmitter in the terminal guidance radar seeker of the anti-ship missile; G_t is the antenna gain of the terminal guidance radar seeker of the anti-ship missile; γ is the polarization mismatch factor; and σ is the radar scatter cross section of the surface warship.

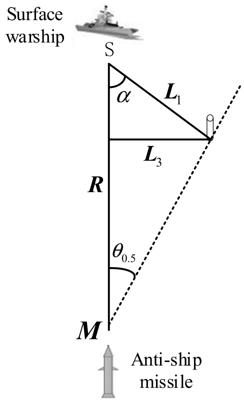

FIGURE 10. Geometrical relationship of off-board jamming at the "critical" position.

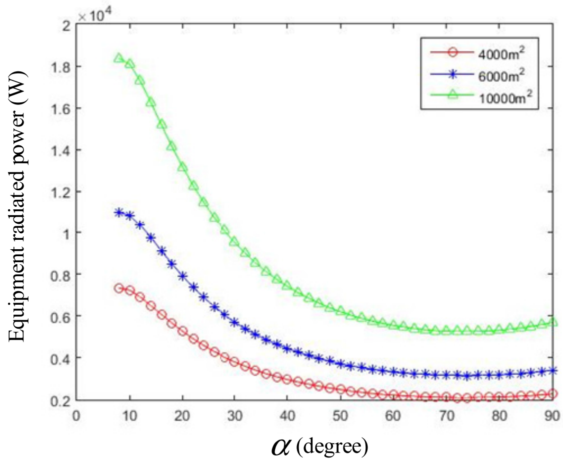

FIGURE 11. Correlation of equivalent radiated power with missile-warship-decoy angle α.

After analyzing Equation (6) for the required equivalent radiated power of the active decoy, it is found that smaller α means lower L_3 when the radar scatter area of the surface warship σ is certain. To achieve a specific jamming blanket factor K_j, the equivalent radiated power of the active decoy P_jG_j must be larger. When the active decoy with the equivalent radiated power P_jG_j satisfies the requirements of Condition 3, there is a lower limit of the missile-warship-decoy angle α at the jamming position of the active decoy. On the contrary, the active decoy at a specific position could only implement the effective centroid jamming against the incoming anti-ship missiles of a specific bearing.

With the parameters $L_1 = 400$m, $P_t = 30$KW, $G_t = 28$dB and $\gamma = 2$, Equations (5) and (6) are used to calculate the jamming blanket factor K_j. Figure 11 presents the correlation of the equivalent radiated power P_jG_j required by the active jamming decoy with the missile-warship-decoy angle α when K_j is 1.5. Obviously, if the equivalent radiated power P_jG_j of the active decoy is certain, the active decoy could protect the area with a smaller angle α when the RCS of the surface warship to be protected is larger. When the equivalent radiated power of the active decoy is 5kW, the

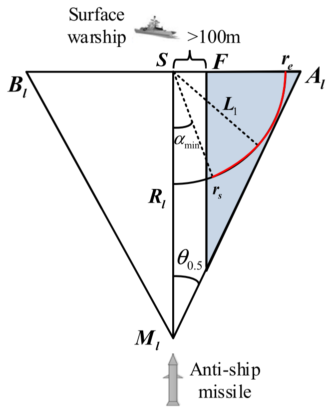

FIGURE 12. Effective deployment area of off-board active decoy under conditions 1, 2 and 3.

active decoy could divert the incoming missiles in the angle range of $35° < \alpha < 90°$ to protect the warship with the RCS of 6000 m^2. When the equivalent radiated power of the active decoy is 10kW, the active decoy could protect the warship with the RCS of 4000 m^2, 6000 m^2 or 10000 m^2 [16] from the incoming missiles in the angle range of $8° < \alpha < 90°$, $15° < \alpha < 90°$ and $30° < \alpha < 90°$ respectively.

In the same way, the feasible interval of missile-warship-decoy angle α with L_1 as the distance from the active decoy and the surface warship is calculated to determine the effective decoy deployment position that satisfies Conditions 1, 2 and 3 simultaneously at this time. It is represented by the arc r_sr_e in Figure 12.

D. FEASIBLE INTERVAL UNDER CONDITION 4

Condition 4 could be satisfied when $\alpha < 90°$.

Following the above way, L_1 is therefore thoroughly scanned in the interval $[0, R_l]$ to obtain the effective deployment position of the off-board active decoy, which satisfies the Conditions 1, 2, 3 and 4.

VI. SIMULATION AND REAL EXPERIMENT VERIFICATION

A. SIMULATION VERIFICATION

Based on the jamming-position maneuver strategy in the previous section, the feasible position area for the USV to collaborate with the surface warship in the implementation of off-board active jamming is calculated in the process as shown in Figure 13. The working and performance parameters of the protected surface warship, the incoming anti-ship missile and the active decoy are input together with the parameters of off-board active jamming conditions to calculate the area that satisfies four conditions simultaneously. The area is the feasible position for active jamming.

Figure 14 shows the feasible position for the ECM USV to provide the off-board active electronic support for the surface warship with RCS=4000 m^2 when the equivalent radiated power of the active decoy is 10kW. In this case, the origin O is the surface warship to be protected; the axis is the line linking the missile to the surface warship; the red area is the feasible area for the off-board active jamming of

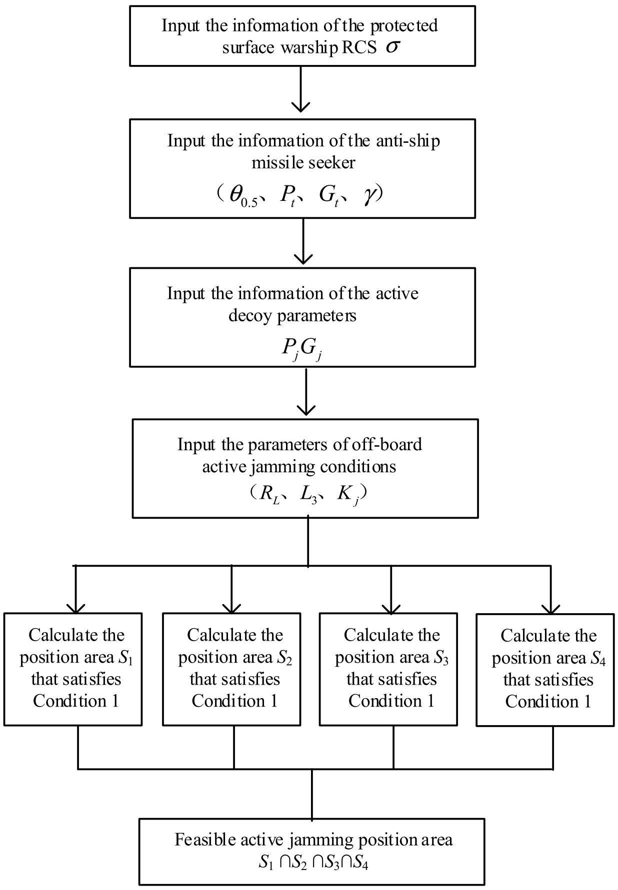

FIGURE 13. Calculation process of feasible active jamming position for USV platform.

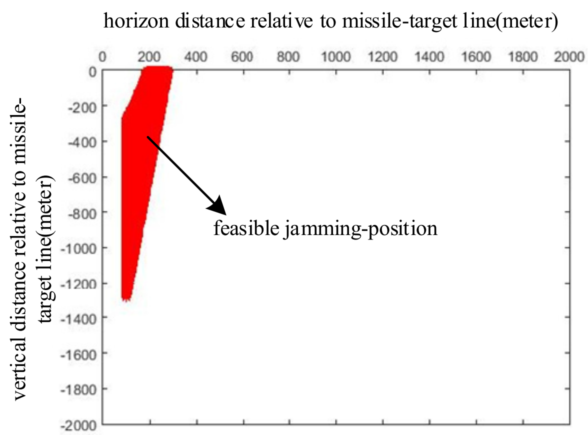

FIGURE 14. Active jamming area of USV platform.

the ECM USV relative to the missile-target line, that is, the jamming position that the ECM USV should maneuver to take. Figure14 presents only the feasible jamming-position area on one side of the missile-target line, but there is still a symmetrical feasible jamming-position area on the other side of the line.

The feasible jamming positions similar to that in Figure 14 could be determined by advance calculating with some typical values, or may be calculated in a real-time manner based on the specific condition of the surface warship to be protected and the anti-ship missile to defend against.

In actual combats, the missile-target line could be calculated using the real-time detected location and motion of the anti-ship missile, so that the feasible jamming-position area is determined. Then, the electronic USV closer to such area is selected and moves fast towards the geometrical center of such area, so as to guarantee the continuous and effective jamming against the incoming anti-ship missile.

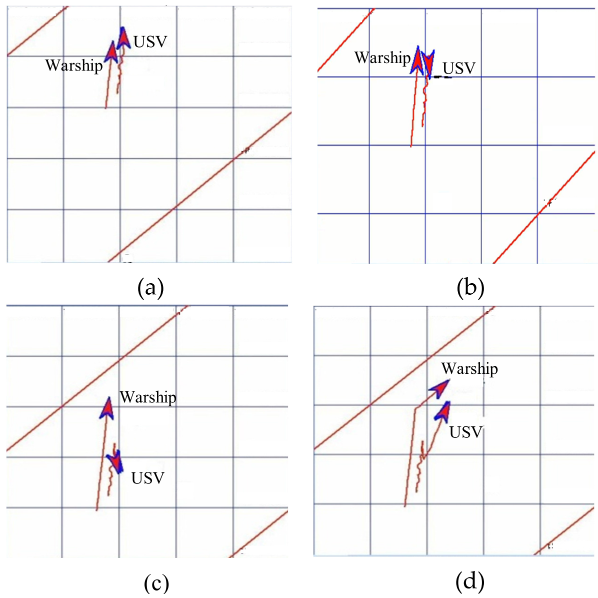

FIGURE 15. Real-time off-board active anti-missile confrontation process of ECM USV. (a) Accounting and escorting; (b) Jamming-position maneuver; (c) Continuous jamming; (d) High-speed collaboration.

B. REAL EXPERIMENT VERIFICATION

The jamming-position maneuver strategy proposed in this paper was tested in a live firing practice with the ECM USV implementing the jamming against two anti-ship missiles salvo. The process is shown in Figure 15. In the anti-missile confrontation process, the ECM USV autonomously escorted the surface warship (the target ship in the practice). After receiving the warning of the incoming missiles and the target indication, the USV implemented the jamming-position maneuver strategy described in the previous section, and moved fast to the feasible jamming area that was calculated in a real-time manner. At the jamming position, the USV utilized the active decoy to perform the off-board active jamming against the incoming missiles. After jamming effect was achieved, the USV collaborated at a high speed with the surface warship to restore the original escort formation, and finally the goal of anti-missile defense with the support of off-board active electronic countermeasure was attained.

VII. CONCLUSION

This paper points out the shortcomings of the existing off-board active radar jamming measures, and proposes a new mode and process of anti-missile combat with off-board active ECM USV. Following the principles of centroid jamming, the real-time calculation method is studied for the feasible jamming position under the off-board active jamming conditions, while the jamming-position maneuver strategy for off-board active ECM USV during the anti-missile combats is put forward. In the end, simulation and live firing confrontations are presented to verify the effectiveness and feasibility of the proposed anti-missile mode and jamming-position maneuver strategy.

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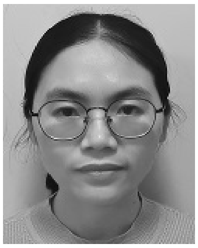

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