Research Article

A Deception Jamming Method Countering Bi- and Multistatic ISAR Based on Micro-Doppler Effect

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Received 15 May 2018; Accepted 28 August 2018; Published 18 September 2018

Academic Editor: Nazrul Islam

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Bi- and multistatic inverse synthetic aperture radar (ISAR) operate with spatially separated transmitting and receiving antennas. A deception jamming method countering bi- and multistatic ISAR is proposed in this paper based on the study of micro-Doppler effect. The jammer modulates the intercepted ISAR signals with added micro-Doppler information and retransmits them to the real target, which scatters the jamming signals to the radar receivers. Deceptive false-target images with interference bands in the cross-range direction will be induced by the jamming signals through the imaging process of radar receivers. Additionally, real-time movement features of the false-targets can be flexibly adjusted by changing the modulation parameters, which improves the fidelity of the false-targets. The equivalent number of looks (ENL) index is used to evaluate the jamming effects. Simulation results validate our theoretical analysis and show the effectiveness and practicability of our method.

1. Introduction

ISAR has been widely used in many military fields such as target classification, enemy recognition, and precision weapon guidance because of its all-day and all-weather surveillance and high-resolution imaging on the target. In the complex electromagnetic environment of modern warfare, bi- and multistatic ISAR have drawn more and more attention due to their advantages in target information acquisition [1], identification, antijamming, and concealment. Bi- and multistatic ISAR can generate high-resolution images of high-speed moving targets with one transmitter and several receivers that are spatially separated. The characteristics of pseudobistatic ISAR system are analyzed by Palmer et al in [2]. Y. Huang et al. discussed the imaging resolution of bistatic ISAR system in [3, 4]. Afterwards, Z.Z. Gao et al. discussed the variation regulations of bistatic angle and equivalent line-of-sight azimuths in the wave-number domain [5]. Bi- and multistatic ISAR show great potential to be widely applied in many military applications.

In recent years, the micro-Doppler effect introduced from laser radar has been developed and utilized in several applications such as feature extraction [6] and the accurate

identification of targets [7, 8]. Meanwhile, with the development of high-resolution time-frequency analysis algorithm [7], the feature extraction algorithm [9] of ISAR targets based on micro-Doppler effect shows great potential [10] in the application of target identification [11]. Micro-Doppler effect also has an impact on the countermeasures to ISAR [12, 13]. The study of bi- and multistatic ISAR countermeasures is scarce according to the literature available [14]. Shi et al. proposed an ISAR jamming idea based on the micro-Doppler effect capable of inducing a train of false-targets in the ISAR images [15]. A method capable of generating deceptive images in the downrange direction of bistatic ISAR based on sub-Nyquist sampling is proposed in [16]. However, this method cannot interfere with the cross-range direction and the features of the false-targets are fixed.

Based on the previous study, a method capable of generating deceptive false-target images with interference bands in the cross-range direction was proposed in this paper. The jammer modulates the intercepted ISAR transmitting signals with added micro-Doppler information and retransmits them to the target, which then scatters the jamming signals to the radar receivers. Deceptive false-target images will be induced near the real target images, as well as interference

FIGURE 1: Geometry of the multistatic ISAR and a target with rotating motion.

bands in the cross-range direction, through the motion compensation and two-dimensional pulse compression imaging process of the radar receivers. The features of the false-target images can be flexibly adjusted to improve the fidelity of the false-targets, so that the decision to engage the target may be delayed even impractically to make without accurate target recognition. Although most of the analyses are directed based on the principle of bistatic ISAR, it can easily be extended to the applications in countering multistatic ISAR for the jamming signals are theoretically scattered in all directions and in all angles.

This remainder of this paper is organized as follows. Section 2 introduces the principle of multistatic ISAR system. Section 3 presents the jamming signal analysis on the basis of the bistatic configuration. Section 4 shows the simulation results together with some performance and key parameter discussion. And the ENL index is utilized to evaluate the jamming effect. Finally, some conclusions are presented in Section 5.

2. Multistatic ISAR System Model and Mathematical Analysis

We show the whole signal processing steps from coherent processing to final image forming in a certain given multistatic system setup. For the purpose of simplicity, suppose that the radar transmitter, receivers, and the jammer are all stationary. The target of multistatic ISAR can be equivalent to a rotating platform model with an angular velocity ω after ideal motion compensation, as in Figure 1. The radar transmitter and receivers are located at T_x , R_{1x} , R_{2x} , and R_{3x} and the instantaneous slant ranges between the target and the radar transmitter and receivers are R_T , R_{R1} , R_{R2} , and R_{R3} , respectively. The bistatic angle of T_x , R_{1x} , and the target is denoted as β . The 2D coordinate xOy is embedded on the target and the origin O is the centre of the moving target. The y -axis is the bisector of angle β and the x -axis is perpendicular to the y -axis. R_p is the range between point scatterer $P(x_0, y_0)$ and O , and θ_p is the included angle between R_p and the x -axis.

M and N are the projection of P in the line of sight of radar transmitter and receiver, respectively.

The LFM signal is widely used as the transmitting signal due to its advantage of enhancing transmit power and widening the bandwidth. Suppose that the transmitting signal of the ISAR transmitter is a linear frequency modulated (LFM) pulse whose central frequency is defined as f_0 and the chirp rate is defined as k . The waveform of the transmitting signal in the fast time and the slow-time domain can be expressed as

$$S(t, t_m) = \text{rect}\left(\frac{t}{\tau}\right) \cdot \exp\left[j2\pi\left(f_0 T + \frac{1}{2}kT^2\right)\right] \quad (1)$$

$$\text{Where } \text{rect}\left(\frac{t}{\tau}\right) = \begin{cases} 1 & |t| \leq 0.5\tau \\ 0 & |t| > 0.5\tau \end{cases},$$

$t = T - m \cdot \text{PRI}$ is the fast time, $t_m = m \cdot \text{PRI}$ is the slow time, τ is the pulse width, m is an integral number, and T is pulse repetition period.

Since $R_p \ll R_T$, R_{TP} , and R_{R1P} can be equivalent to R_{TM} and R_{R1N} , respectively. Suppose that the sum of ranges from the point O to the radar transmitter and receiver (bistatic range) is R_0 and the bistatic range of point scatterer P is

$$\begin{aligned} R_P(t_m) &\approx R_{TM} + R_{R1N} = R_T + R_{R1} + OM(t_m) \\ &- ON(t_m) = R_0 + OP \left(\cos\left(\frac{\pi}{2} - \frac{\beta}{2} - (\theta + \omega t_m)\right) \right. \\ &\quad \left. - \cos\left(\frac{\pi}{2} - \frac{\beta}{2} + (\theta + \omega t_m)\right) \right) \end{aligned} \quad (2)$$

The rotation angle of target is negligible during the processing time of radar imaging, therefore has $\sin(\omega t_m) \approx \omega t_m$ and $\cos(\omega t_m) \approx 1$, and then (2) can be expressed as

$$\begin{aligned} R_P(t_m) &= R_0 + 2OP \cdot \sin(\theta_p + \omega t_m) \cos \frac{\beta}{2} \\ &= R_0 + 2OP \\ &\quad \cdot (\sin \theta_p \cos(\omega t_m) + \cos \theta_p \sin(\omega t_m)) \cos \frac{\beta}{2} \\ &= R_0 + y_o \cos \frac{\beta}{2} + x_o \omega t_m \cos \frac{\beta}{2} \end{aligned} \quad (3)$$

and thus the echo signals of point scatterer P collected by radar receiver R_{1x} are

$$\begin{aligned} S_P(t_m) &= \sigma_P \cdot \text{rect}\left(\frac{t}{\tau}\right) \cdot \exp\left(-\frac{j2\pi f_0}{c}\right. \\ &\quad \left. \cdot \left(R_0 + 2y_o \cos \frac{\beta}{2} + 2x_o \omega t_m \cos \frac{\beta}{2}\right)\right) \end{aligned} \quad (4)$$

σ_P is the scattering coefficient of P. Carrying out the Fourier transform (FT) in the slow-time domain, then the Doppler frequency of point scatterer P has a form as

$$f_D = \frac{4\pi\omega f_0 x_0}{c} \cos \frac{\beta}{2} \quad (5)$$

It can be seen from (5) that the Doppler frequency of each point scatterer of the target is proportional to its position in the range direction. The use of spectrum analysis methods such as FT can separate different point scatterer in each range resolution cell. Thus the range-Doppler image of the target can be obtained.

The imaging principle of other radar receivers is same as Rlx.

3. Jamming Signal Analysis

Without loss of generality, a bistatic configuration is used to analyze the jamming signal, as in Figure 2. Denote the radar transmitter, receiver, and the jammer T_x , R_x , and J_x , respectively. The jammer modulates the intercepted ISAR transmitting signals with added micro-Doppler information and retransmits them to the target. Therefore the jammer and the radar receiver can be equivalent to a bistatic ISAR system with a bistatic angle denoted as β . The 2D coordinate xOy is embedded on the target and the origin O is the centre of the target. The y-axis is the bisector of β and the x-axis is perpendicular to the y-axis. Denote the false rotating point scatterer

as $P(x_p, y_p)$ and it is rotating centre as O_1 . P has both the same translational movement as point O_1 and the rotational movement with a radius denoted as R_p in the xOy plane. Additionally, the initial phase and the angular velocity of P are denoted as θ_p and ω_p , respectively. M and N are the projections of P in the line of sight of the jammer and radar receiver. Denote the initial angle included in R_p and the x-axis as θ .

The jammer generates deception jamming signals through three steps: intercepting, modulating, and retransmitting. Suppose that the radar transmitting signal is same as Section 2.

The bistatic range of P can be written as

$$\begin{aligned} R_P(t_m) &\approx R_{JM} + R_{RIN} = R_J + R_{R1} + OM(t_m) \\ &- ON(t_m) + R_P \cos(\omega_p t_m + \theta_p) - R_P \\ &\cdot \sin(\omega_p t_m + \theta_p) = R_O \\ &+ R_{OO_1} \left(\cos\left(\frac{\pi}{2} - \frac{\beta}{2} - (\theta + \omega t_m)\right) \right. \\ &- \cos\left(\frac{\pi}{2} - \frac{\beta}{2} + (\theta + \omega t_m)\right) \Big) \\ &+ R_P (\cos(\omega_p t_m + \theta_p) - \sin(\omega_p t_m + \theta_p)) \end{aligned} \quad (6)$$

t_m is the slow time. Then the jamming signal modulated by the jammer can be expressed as

$$\begin{aligned} S_P(t_m) &= \sigma_P \cdot \text{rect}\left(\frac{t}{\tau}\right) \cdot \exp\left(-\frac{j2\pi}{c}\right. \\ &\cdot \left(R_O + R_{OO_1} \left(\cos\left(\frac{\pi}{2} - \frac{\beta}{2} - (\theta + \omega t_m)\right) - \cos\left(\frac{\pi}{2} - \frac{\beta}{2} + (\theta + \omega t_m)\right) \right. \right. \\ &\left. \left. + R_P (\cos(\omega_p t_m + \theta_p) - \sin(\omega_p t_m + \theta_p)) \right) \right) \end{aligned} \quad (7)$$

Carrying out the FT in the slow-time domain, then the Doppler frequency of P has a form as

$$f_{MD} = \frac{4\pi\omega R_P x_1}{\lambda} \cos \frac{\beta}{2} \sin(\omega_p t_m + \theta_p) \quad (8)$$

It can be seen from (8) that when the target scatters the jamming signals to the radar receiver, false-target images with micro-Doppler features are induced in the ISAR images. The false-target images rotate at an additional angle which equals $\beta/2$ compared with the real target images. And the false micro-motion points will induce interfere bands in the cross-range direction.

4. Simulations and Image Result Analysis

4.1. Simulation Description. A plane model of 74 point scatterers is adopted to demonstrate the effect of the jamming idea which takes up to 20m (downrange) $\times$ 20m (cross-range). The simulation process is described in Figure 3.

Simulation parameters are listed in Table 1. The radar is assumed operating at 10GHz (f_0) and transmitting a LFM

waveform with 1GHz bandwidth (B). The pulse width (τ) is 10 μ s and the pulse repetition frequency (PRF) is 200Hz. A total of 512 pulses are transmitted. Values of R_{T0} , R_{J0} , and R_{R10} are set as 50km, 60km, and 70km, respectively, which satisfy the approximation of far-field back scattered field. The bistatic angle (β) is 120°. The transmitting power (P_J) of the jammer is 140W and the antenna gain (G_J) is 30dB. The rotating angular velocity (ω) of the target is 0.02rad/s.

4.2. Image Result. Figure 4(a) shows the range-Doppler image of the plane model. The single and multiple false-target images of ordinary deception jamming method are illustrated in Figures 4(b) and 4(c), respectively. It can be seen that the false-target images are distributed in different range cells but the Doppler frequency of each false-target is the same.

Figure 4(d) depicted a single false-target image with two rotating micro-motion points, whose rotation radius is 3m and the angular velocity is 20rad/s. The false-target image rotates an additional angle of 60° ($\beta/2$) compared with

FIGURE 2: Geometry of the Jamming Scenes.

FIGURE 3: Simulation process.

TABLE 1: Simulation parameters.

f_0/GHz	10	R_{R10}/km	70
B/GHz	1	R_{J0}/km	60
$\tau/\mu\text{s}$	10	P_J/W	140
PRF/Hz	200	G_J/dB	20
N	512	$\omega/\text{rad}\cdot\text{s}^{-1}$	0.02
R_{T0}/km	50	$\beta/^\circ$	120

Figure 4(b) and has two interference bands in the cross-range direction, which verifies the conclusions in Section 3.

In order to flexibly control the image features and motion information of the false-target, we further studied the jamming effect with the changing of certain parameters compared to Figure 4(d), and the simulation results are shown in Figures 4(e)–4(h). In Figure 4(e) the equivalent bistatic angle is reduced to 60° and as a result the false-target image rotates 30° . In Figure 4(f) the rotation radius of the micro-motion points has increased to 5m; it can be seen that the width of the interference bands has broaden. Figure 4(g) illustrates the false-target image when the jammer's retransmitting time delay reduced to 60ns. And Figure 4(h) illustrates the false-target images with the angular velocity of micro-motion points reducing to 10rad/s. It can be seen that the sparse degree of interference bands has decreased.

Compared to Figure 4(c), the image of multiple false-target and micro-motion points was depicted in Figure 4(i). It can be seen that the real target image was hidden within the false-targets images and interference bands, making it difficult for ISAR to distinguish.

Through the above simulation, we can arbitrarily set the position, number, and movement information of the false-target and the micro-motion point scatterers according to the operational needs, which greatly improves the fidelity of deception jamming.

4.3. Analyses of Jamming Effect. The equivalent number of looks (ENL), which is an indicator of the grayscale of an image's pixels, is used to analyze the jamming effect. It is the most commonly used standard for image evaluation and is defined as the ratio of the mean of the image to the standard deviation of the image:

$$ENL = \frac{\bar{\mu}}{\sqrt{\sigma^2}} \quad (9)$$

The mean value of the image reflects the average gray level of the image. The standard deviation of the image represents the degree of deviation of all points in the image area from the average, which reflects the nonuniformity of the image. There will be big changes of the mean and standard deviation of the ISAR images when they are jammed. The bigger the changes are, the more significant the jamming effect is. The ENLs of the images in Figure 4 are listed in Table 2.

It can be seen that the jamming method proposed in this paper has a more significant effect on ISAR images in both cases of single and multiple false-target deception jamming than ordinary deception jamming method.

5. Conclusions

The novelties of this paper are that multiple false-target images with additional micro-Doppler information will be induced by the jamming signals. Additionally, the real-time movement features of the false-target images can be flexibly adjusted as needed. Multiple false-target images which are similar to the real target can increase the cost burden and waste the finite resource of radar for identifying the real one. The deceptive jamming method could have a negative impact on the ISAR target recognition applied to aircrafts, ships, and missiles.

Data Availability

Data is obtained by computer simulation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the China Postdoctoral Science Foundation under Grant 2017M623123.

FIGURE 4: Image Results for different parameter values.

TABLE 2: ENLs of the image results in Figure 4.

Image number	ENL	mean value	standard deviation
Figure 4(a)	3.6537	23.1853	6.3457
Figure 4(b)	4.8865	39.8606	8.1573
Figure 4(c)	6.0223	59.5701	9.8916
Figure 4(d)	5.3407	45.3751	8.4961
Figure 4(e)	5.3227	45.1859	8.4893
Figure 4(f)	6.1563	64.9237	10.5458
Figure 4(g)	5.3078	45.1247	8.5016
Figure 4(h)	5.5369	46.9147	8.4731
Figure 4(i)	8.5110	125.9509	14.7986

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