Recognition method of dense false targets jamming based on time-frequency atomic decomposition

Zhimei Hao\textsuperscript{1}, Wen Yu\textsuperscript{1}, Wei Chen\textsuperscript{1}
\textsuperscript{1}School of Electronic Information Engineering, Beihang University, Beijing, People’s Republic of China
\textsuperscript{E-mail: haozhimei@buaa.com}

Abstract: Dense false target jamming can affect radar detection performance severely. A method of dense false targets jamming recognition based on time-frequency atomic decomposition theory and support vector machine (SVM) is proposed to solve the difficulty of dense false targets jamming identification. According to the feature of ambiguity function of dense false targets jamming signal, a Gabor sub-dictionary which has adaptive variation with signal is designed. The signal is expanded into the corresponding Gabor time-frequency dictionary by sparse decomposition. After Gabor atomic time-frequency parameters are extracted as individual feature vectors, SVM is utilised for classification and recognition. The experimental results show that the extracted Gabor atomic time-frequency parameters can effectively represent the essential features of target and dense false targets jamming, respectively, and this method has a high recognition rate.

1 Introduction
In recent years, the rapid development of modern electronic jamming technology and equipment has impaired radar detection function seriously. To improve anti-jamming ability has become an important topic in radar research. Jamming type recognition is the core problem in radar anti-jamming design. Dense false targets jamming is a new type of deceptive jamming which is specially used to counter pulse compression radar. Digital radio frequency memory (DRFM) is used to collect, store, copy, and transmit signals to implement this type of jamming [1]. Dense false targets jamming produces a large number of false targets which are similar to target signals at the radar receiver [2, 3]. It can interfere with normal detecting and tracking of real targets because of deceptive and suppressive jamming effects. Dense false targets jamming has strong characteristics of concealment. Smeared spectrum (SMSP) and chopping and interleaving (C&I) jamming presented by Sparrow [4] are two new types of dense false targets jamming, which can be realised by DRFM. SMSP and C&I jamming have a high correlation with radar signals. They can obtain higher pulse compression gain and cause a large number of false alarm. These two kinds of jamming deceive radar operators and systems and pose a great threat to modern pulse compression radar. This will certainly bring new challenges to the identification and suppression of dense false targets jamming.

As to the type recognition of deception interference, domestic and foreign scholars have done extensive and deep research on the feature differences between target signal and jamming signal in time domain, frequency domain [5], polarisation domain [6] etc. However, jamming recognition methods are mainly focused on traditional deceptive jamming [7, 8]. Researches on new types of deceptive jamming recognition are less. Furthermore, with the increase of the DRFM amplitude and phase quantisation bit number, the feature differences between target and jamming signal extracted from a single dimension are less obvious, which affects the interference recognition.

To solve the problem of feature extraction and recognition of new dense false target jamming, a novel feature extraction method based on adaptive Gabor sub-dictionary is proposed from time-frequency joint domain in this paper. This method is based on the ambiguity function feature of dense false target jamming signal. The signal is expanded into the corresponding Gabor time-frequency dictionary through sparse decomposition, and Gabor atomic time-frequency parameters are extracted as individual feature vectors. Then, the SVM classifier is used to carry out classification experiments. As to traditional methods, there is no obvious difference of extracted feature between target and jamming signal in single dimension, and the interference recognition result is not satisfying. This paper solves the drawbacks of traditional methods and performs effectively in jamming recognition.

2 Time-Frequency signal model analysis of dense false targets jamming
2.1 Model of SMSP jamming
We assume here that the radar transmits a linear frequency modulated (LFM) signal. The complex envelope of LFM is given by:

\[ S_f(t) = \exp\{j2\pi(f_0 + 0.5kt^2)t\}, 0 \leq t \leq T \]

(1)

where \(f_0\), \(B\) and \(T\) are the central frequency, the bandwidth, and the pulse width of the signal, respectively. \(K = B/T\) is the chirp rate.

The radar transmitted signal is intercepted by the jamming system. The jamming system uses DRFM technology and digital signal processor as its main control centre, which can produce new types of jamming with complicated modulation parameters. The SMSP jamming is composed of \(n\) sub-pulses. The time width of each sub-pulse is \(1/n\) of the transmitted signal. The FM rate of each sub-pulse \(k'\) is \(n\) times more than the radar transmitted signal, and the jamming bandwidth is the same as the bandwidth of the radar LFM signal.

The model of SMSP jamming is:

\[ J_{SMSP}(t) = \sum_{i=0}^{n-1} J(t - i\frac{T}{n}), 0 \leq t \leq T \]

(2)

\[ J(t) = A_i \exp(j2\pi(f_i t + 0.5k' t^2)), 0 \leq t \leq T/n \]

(3)

where \(A_i\) and \(k' = nk\) are the amplitude and the FM rate of jamming signal, respectively. According to formula (2) and (3), the time width and bandwidth of SMSP jamming are identical with the radar transmitted signal. SMSP jamming can generate a large amount of false range targets at the receiving end of radar.
2.2 Model of C&I jamming

Radar transmitted signals are intercepted and stored by the jamming system. Then, the C&I jamming is generated through intermittent sampling and repeated duplication of radar transmitted signals. A schematic diagram of C&I jamming is shown in Fig. 1.

According to Fig. 1, the mathematical model of C&I jamming is:

\[
J(t) = \sum_{j=0}^{n-1} P(t - jT/n) A_j(t) X(t)
\]

\[
P(t) = A_j(t) X(t)
\]

where \( A_j(t) \) is the amplitude of jamming signal, \( T_e \) is the sampling pulse width, \( T_s \) is the sampling pulse interval, \( n \) is the number of replicas in each sampling fragment, \( m = T/T_s \) is the number of sampling pulse train. According to formula (4) and (5), the time width and bandwidth of C&I jamming are identical with the radar transmitted signal. C&I jamming can also create a large amount of false range targets at the receiving end of radar.

3 Feature extraction of dense false targets jamming based on time-frequency atomic decomposition

3.1 Time-frequency atomic decomposition

It is an effective way to classify and recognise the dense false targets jamming through the extraction of the time-frequency joint features from radar echoes. Traditional time-frequency analysis methods mainly include short time Fourier transform, Wigner distribution etc. However, the time-frequency concentration of the traditional time-frequency analysis is affected by the window function selection. Meanwhile, the dimension of extracted time-frequency jamming features is higher [9]. The method of time-frequency atomic analysis describes signals by establishing an overcomplete dictionary and choosing less basis functions from it. The construction method of the overcomplete atom dictionary can be realised through the expansion, modulation, and translation of the window function \( g(t) \).

Gabor dictionary is defined as a complete set of Gabor atoms. As Gabor has the best time-frequency concentration, the time-frequency characteristics of the signal can be better revealed by using Gabor dictionary to decompose the signal.

Gabor atom is a modulated Gauss function. Its mathematical expression is:

\[
g(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(t-u)^2}{s^2}} \cos(vt+\phi)
\]

where \( g(t) \) is Gauss function. It can be seen from formula (6) that each Gabor atom can be described by parameter \( r = (s, u, v, \phi) \) where \( s \) is the time scale, \( u \) is the time centre, \( v \) is the central frequency, \( \phi \) is the phase). This paper builds a discrete Gabor dictionary \( D_a(D_a = \{g_r(t)\}_{r \in T_a}) \), where parameter set \( T_a \) is defined as \( r = (\alpha^j, \alpha^j \Delta u, \alpha^j \Delta v, j\Delta \phi) \), and \( \alpha = 2, \Delta u = 0.5, \Delta v = \pi, \Delta \phi = \pi/6, 0 < j \leq \log_2 N, 0 \leq p \leq N \cdot 2^{-j+1}, 0 \leq k < 2^{j+1}, 0 \leq i \leq 12 \) The signal decomposition on the overcomplete dictionary must be sparse. Matching pursuit (MP) algorithm is one of the algorithms to realise the sparse representation of signals on an overcomplete dictionary. Let \( H \) be Hilbert space, and \( D_a \) is an overcomplete dictionary in \( H \). Atom \( g_r(t) \) is described by parameter \( r, r \in T_a \). Assuming that the signal \( f \) is to be analysed, and \( f \in H \) can be decomposed into:

\[
f = \sum_{n=0}^{m-1} \{R^n f, g_r\} g_r + R^n f
\]

where \( R^n f \) is the residual signal after the \( n \)th iteration, \( g_r \) is the atom which matches residual signal \( R^n f \) in the \( n \)th iteration in atom dictionary. Also, \( g_r \) meets the condition:

\[
||R^n f, g_r|| \leq \alpha \sup_{r \in T_a} ||R^n f, g_r|| \quad 0 < \alpha \leq 1
\]

In each iteration, MP algorithm selects the atom which matches the residual signal from the atomic dictionary and then subtracts the atom component from the residual signal to get a new residual signal. When the residual signal’s energy is lower than a certain threshold or satisfies other stopping conditions, the iterative process ends.

3.2 Feature extraction of dense false targets jamming

When the signal length is long, the traditional MP method has large computing quantity in atomic search. In this paper, a feature extraction technique of dense false targets jamming based on Gabor atomic decomposition is proposed. This technique uses the periodic characteristics of SMSP and C&I jamming. First, autocorrelation pre-processing is taken on the radar echo. Second, key parameters are extracted on the basis of pre-processing and a subset of the Gabor atom dictionary is constructed. At last, MP algorithm is utilised to seek a matching time-frequency atom. The extracted parameter information about the best atom is used for classification and recognition.

The feature extraction of SMSP and C&I jamming includes three steps.

Step 1: The pre-processing technology mainly completes the autocorrelation process of jamming signals, and autocorrelation function can reflect the periodicity of the signal.

The \( n \)th and \( p \)th sub-pulse are chosen arbitrarily to process correlation, then the autocorrelation function of SMSP jamming can be obtained as: (see (11))

\[
|\hat{f}(n, p)| \leq (|p-l|+1/m)|T| + (|q-i|+1/m)|T|
\]

where \( |\hat{f}| \) is \( |(m+1-p)/m)|T| + (q-i+1/|m)|T| \).
Step 2: The repetition interval $n$ and time width of each jamming pulse $L$ ($L = T/n$) are extracted according to pre-processing. A discrete and adaptive Gabor sub-dictionary $D_{g}(D_{a} = \{g(t)\}_{t \in T})$ is constructed. The parameter set $T_{a}$ is defined as $r = (a_{1}, a_{2} \Delta t, 2\Delta v, i \Delta \varphi)$. Also, the range of parameters are redefined as: $a_{2} = 2$, $\Delta t = 0.5$, $\Delta v = 0.5$, $\Delta \varphi = \pi/6$, $0 < j \leq \log_{2}L$, $0 \leq p \leq N \cdot 2^{j+1}$, $0 \leq i \leq 12$, $f_{\text{min}}/f_{\Delta v} \leq k < f_{\text{max}}/f_{\Delta v}$, where $f_{\text{max}}$ and $f_{\text{min}}$ are maximum and minimum frequencies of echo signal.

Step 3: In each iteration, MP algorithm is adopted to select the atom which matches the residual signal from the adaptive Gabor sub-dictionary and then subtracts this atom component from the residual signal to gain a new residual signal. When the residual signal's energy is lower than a certain threshold or satisfies other stopping conditions, the iteration ends.

4 Simulation

This section will evaluate the proposed recognition method of dense false targets jamming based on Gabor atomic decomposition through simulation experiments. The classifier used in simulation is SVM classifier. SVM classifier is a kind of kernel function classifier which is widely applied to pattern recognition. SVM is developed from the optimal hyperplane under the linearly separable condition. By mapping the input from a low-dimensional space to a high-dimensional space, the linear learning machine is used to solve the regression and non-linear classification problem of sample space in SVM.

Assuming that radar transmits LFM signals, intermediate frequency is 10 MHz, pulse width is 10 μs, LFM bandwidth is 10 MHz, and sampling rate is 100 MHz. SMSP jamming consists of four sub-pulses, FM rate is 4 MHz/μs. The sampling pulse time width of C&I jamming is 1 μs, sampling pulse interval is 3 μs. Each fragment has three replication. Pulse compression, time-frequency analysis, and autocorrelation function simulation of radar signals, SMSP jamming and C&I jamming are conducted, respectively. The results are shown in Figs. 2 and 3.

It can be seen from Figs. 2a and 3a that SMSP and C&I jamming can form dense false targets jamming after radar matching filter. Figs. 2b and 3b indicate that SMSP and C&I jamming are different from radar signal in time-frequency distribution. SMSP and C&I jamming have relatively lower time-frequency resolution compared to radar signal. As to SMSP jamming, the peak number and distance between peaks are associated with sub-pulse's number and time width according to Fig. 2c. The ambiguity function of SMSP jamming has 2n-1-peaks in total. The distance between each peak is equal to the time width of echo signal in each sampling fragment $T/n$. Therefore, each jamming's pulse time width $T/n$ and repetition interval $n$ of SMSP jamming can be calculated based on formula (10). The time width of each sampling pulse $T/n$ and the number of replicas in each sampling fragment $n$ can be calculated from formula (11).

The ambiguity function of C&I jamming has 2n-1-peaks in total. The distance between each peak is $T/n$. Meanwhile, the ambiguity function of C&I jamming has 2n-1-peaks in total. The distance between each peak is $T/n$ according to Fig. 3c.

Gabor atomic decomposition is adopted to obtain SMSP and C&I jamming atoms in Gabor dictionary. The reconstruction time-frequency graphs are shown in Figs. 4 and 5. It can be seen from Figs. 4 and 5 that Gabor atoms achieved by decomposition form the component of each signal. Selecting the Gabor atom with larger...
As to SMSP and C&I jamming, SVM classification is utilised to conduct 100 jamming recognition experiments under condition of each jamming to noise ratio. The average jamming recognition rate is shown in Fig. 6. The jamming recognition rate increases with the rise of jamming to noise ratio according to Fig. 6. The jamming recognition rate reaches over 90% when the jamming to noise ratio is >10 dB.

5 Conclusions

The dense false targets jamming poses a great threat to modern radar system. It not only produces a large number of false alarm to disturb the normal work of radar, but also makes it difficult for radar to find the real targets and affects the range of detection seriously. The accurate identification of dense false targets jamming can provide foundation for further valid anti-jamming measures adoption. In this paper, a method of dense false targets jamming recognition based on Gabor atomic decomposition is proposed. This method first extracts the autocorrelation function of the jamming signal, and then adaptively constructs the time-frequency atom sub-dictionary by using the prior knowledge, which can quickly and efficiently extract the time-frequency features of the dense deception jamming. The simulation results show that the features of dense false targets jamming extracted from Gabor atomic decomposition are robust at low jamming to noise ratio, and the effectiveness of the proposed method is proven by SVM classification experiments.
6 References

[1] Kwak, C.M.: ‘Application of DRFM in ECM for pulse type radar’. 34th Int. Conf. on Infrared, Millimeter, and Terahertz Waves, Busan, South Korea, 2009, pp. 1–2

[2] Greco, M., Gini, F., Farina, A., et al.: ‘Effect of phase and range gate pull-off delay quantisation on jammer signal’, IEEE Proc.-Radar Sonar Navig., 2006, 153, (5), pp. 454–459

[3] Berger, S.D.: ‘Digital radio frequency memory linear range gate stealer spectrum’, IEEE Trans. Aerosp. Electron. Syst., 2003, 39, (2), pp. 725–735

[4] Mitchell, J.S., Joseph, C.: ‘ECM techniques to counter pulse compression radar’. United States Patent, 7081846, 2006

[5] Yunlong, L., Ming, L., Yan, Y.: ‘Method for detecting DRFM deception jamming based on LFM rate matching’, J. Xidian Univ., 2014, 41, (5), pp. 67–73

[6] Yongzhen, L., Xujian, S., Liandong, W., et al.: ‘Polarization identification algorithm of active-decoys and radar targets based on sidelobe-canceller antenna’, Signal Process., 2008, 24, (1), pp. 24–27

[7] Minghong, S., Bin, T.: ‘Feature extraction of radar deceptive-jamming signal based on atomic decomposition’, Chinese J. Radio Sci., 2008, 23, (3), pp. 550–554

[8] Faruk, K., Yakup, O.: ‘A method for detecting RGPO/VGPO jamming’. Signal Processing and Communications Applications Conf., Proc. of the IEEE 12th, Kusadasi, Turkey, Turkey, 2004, pp. 237–240

[9] Aifang, L., Xiaohua, Z., Zhong, L.: ‘Multicomponent LFM signal detection and parameter estimation based on radon-gabor transform’, J. Electron. Inf. Technol., 2004, 26, (2), pp. 220–224

Fig. 6 Jamming recognition rate varies with the jamming to noise ratio.

This is an open access article published by the IET under the Creative Commons Attribution -NonCommercial License (http://creativecommons.org/licenses/by-nc/3.0/)