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Radar system simulation and non-Gaussian mathematical model under virtual reality technology

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Abstract

The characteristics of non-Gaussian clutter in radar systems are different from standard waveforms. To fully filter to achieve the accuracy of radar detection, the paper developed a radar simulation system based on virtual reality technology. The article uses a non-Gaussian mathematical model to simulate and collect the clutter generated by the system and realise the generation of data sequence according to the power spectrum. The research results show that the radar cross-section modelling, target recognition, anti-recognition and data fusion technology of visible targets can all be well applied in this system.

Keywords: Virtual reality; radar system; non-Gaussian clutter; system simulation.

AMS 2010 codes: 60G15

1 Introduction

In radar imaging and evaluation research, the technology is developed based on virtual reality. Today, radar systems are becoming more complex, and equipment costs are more expensive. We can use virtual reality technology to test, train an. This will not only improve efficiency in an all-around way but also effectively reduce costs. Real-time, high-fidelity imaging simulation, whether for military or civilian use, has a wide range of needs and huge application prospects [1]. Because the visual model of the radar system has its characteristics, the constructed model covers terrain, landforms, human landscapes and a vast geographic area. This leads to many polygons generated by the model, which places high requirements on the hardware. There is also a contradiction between authenticity and real-time. The development of a radar simulation system requires simulation users, modellers, software developers, testers and evaluators to work together. The traditional approach is to simulate user requirements/modellers with radar expertise abstract the actual system to establish a mathematical

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model/software and the developers complete programming based on the mathematical model/test and evaluate the software.

Most of the actual radars perform detection based on multiple pulse signal observations. The accumulated clutter samples are correlated [2]. Therefore, in the clutter signal simulation, we need to consider the probability distribution of the clutter amplitude and its related characteristics simultaneously. In general, the clutter signal can be represented by a narrowband random process, namely

$$X_{RF}(t) = \text{Re}[X(t)e^{j\omega X}] \quad (1)$$

where $X(t)$ is the complex envelope. It has the form

$$X(t) = x_i(t) + jx_q(t) = A(t) \exp[j\theta(t)] \quad (2)$$

$x_i(t)$ and $x_q(t)$ are the in-phase component and the quadrature component, respectively. $A(t)$ is the envelope or amplitude random process. $\theta(t)$ is the random phase process. The statistical characteristics of clutter refer to two aspects: the probability density distribution of $A(t)$ and the correlation characteristics of $X(t)$. Where the relevant characteristics are expressed as

$$r_x(t, \tau) = E[X(t)X^*(t - \tau)] \quad (3)$$

* is the complex conjugate operation. $E()$ is the calculation of the statistical average. $r_x(t, \tau)$ is called the autocorrelation function (ACF) of $X(t)$. It is known from the nature of the Fourier transform that the power spectrum characteristics of the autocorrelation function $r_x(t, \tau)$ and the clutter $X(t)$ are a Fourier transform pair. Therefore, the correlation characteristics of the clutter can also be determined by its power spectrum characteristics.

In the early radar system, due to the low resolution of the radar, the radar clutter was considered to echo a large number of approximately equal independent unit scatterers superimposed on each other. According to the central limit theorem, it is found that the process of superposition can be regarded as a Gaussian process, so the amplitude distribution characteristics of the clutter obey the assumption of the Gaussian distribution model. Thus, we require a large number of independent scatterers [3]. However, the resolution of modern radars is getting higher and higher, which makes the echoes of adjacent scattering units have a specific correlation in time and space. So the above assumption is no longer valid. And many measured data have also been confirmed. In the case of low-elevation or high-resolution radars, the statistical characteristics of the clutter distribution deviate from the Gaussian distribution characteristics. Therefore, there are amplitude distribution characteristics of the environmental clutter of modern radars. Therefore, the non-Gaussian distribution model can simulate the statistical characteristics of the actual radar echo more accurately. The commonly used non-Gaussian amplitude density distribution models mainly have three forms: Weibull distribution, lognormal distribution and K distribution.

The method of quickly and accurately simulating radar clutter is fundamental in designing the optimal signal processor of the radar and the simulation of the radar system. So far, the simulation methods of related non-Gaussian clutter mainly include the spherical invariant random process (SIRP) method and the memoryless nonlinear transformation method (ZMNL).

2 Memoryless nonlinear transformation (ZMNL) model of generalised Wiener process

Some scholars have proposed a method of simulating K-distributed radar clutter with the SIRP method. The basic idea is to design an FIR filter based on the actual collected radar clutter data. The white noise generates a correlated Gaussian random process through the filter and then modulates it with a random variable S with the required single-point probability density function [4]. This method is limited by the order of the sequence and

the autocorrelation function. Not all clutter amplitude statistical characteristic models can find the corresponding modulation variable S . At the same time, this method has a considerable calculation. It is not easy to form a fast algorithm. The ZMNL of the generalised Wiener process makes up for the shortcomings of the SIRP method. It can realise the signal simulation of various commonly used statistical models. The generalised Wiener process directly applies the simple Wiener process with a specified first-order probability density function and related characteristics in the complex number sequence. The basic principle of the ZMNL method is shown in Figure 1.

Fig. 1 Memoryless nonlinear transformation method

According to modern signal theory, the relevant Gaussian clutter can be regarded as the response when a white Gaussian clutter with a mean value of zero is applied to a digital filter. The excitation signal $W(k)$ is an independent white spectrum complex Gaussian process with a mean value of zero. $Y(k)$ is a random sequence whose spectral characteristic is Gaussian spectrum, and the probability density function of its amplitude $A_Y(k)$ obeys the Rayleigh distribution. $X(k)$ is the relevant complex wave signal that needs to be simulated.

After $W(k)$ passes through the linear filter $H(z)$, the relevant characteristics required by $X(k)$ are introduced [5]. The memoryless nonlinear transformation (ZMNL) changes the probability density function of the amplitude of $Y(k)$ the desired signal $X(k)$ and keeps the $Y(k)$ phase process $\theta(k)$ unchanged. After ZMNL transformation, the autocorrelation function $r_Y(m)$ of $Y(k)$ and the autocorrelation function $r_X(m)$ of $X(k)$ inevitably have a particular nonlinear relationship, namely

$$r_X(m) = g[r_Y(m)] \quad (4)$$

$g(\bullet)$ represents the nonlinear relationship between $r_X(m)$ and $r_Y(m)$. In this way, the analytical relationship of $r_Y(m)$ can be obtained from Eq. (4). Under certain conditions $H(z)$, can be obtained from $r_Y(m)$ through spectral decomposition. Although the ZMNL method is relatively classic and the corresponding $g(\bullet)$ relationship is very complicated, the ZMNL transformation relationship of various standard clutter models has been found after the research has obtained the ZMNL analytical relationship of the K distribution [6]. Therefore, the ZMNL method of the generalised Wiener process is a general and convenient clutter simulation method. Therefore, we use the ZMNL model method to simulate the correlated non-Gaussian distribution clutter signal.

3 The ZMNL radar clutter simulation system

We propose a multi-functional simulation analysis system based on the memoryless nonlinear transformation (ZMNL) model of the generalised Wiener process. The block diagram is shown in Figure 2. We define $a(k)$ as the coefficients of each order of the AR model. $y(n)$ is a sequence of correlated Gaussian processes with zero means. The amplitude envelope of the output-related clutter $x(n)$ obeys the required probability density distribution. Some scholars have given the corresponding relationship between y and the autocorrelation function $r_X(m)$ of x of various distributions, namely $g[\cdot]$. In addition, some scholars have listed the ZMNL transformation relations of various clutter statistical models.

Fig. 2 Block diagram of the clutter simulation system

According to the inference of WOLD decomposition theory, any ARMA or AR process can be represented by an infinite-order MA model. An infinite-order AR model can represent any ARMA or MA process. Because, the AR model is suitable for the power spectrum form with sharp peaks but no deep valleys and the MA model is suitable for the power spectrum form with deep valleys but no peaks. Therefore, the AR model is generally used to simulate the relative power spectrum characteristics of the radar clutter [7]. The system can dynamically simulate the actual collected radar clutter in real time and generate various distributed cluster data according to the clutter power spectrum required by the user.

4 Radar system simulation framework based on virtual reality technology

Radar system models can be divided according to different granularities and levels [8]. However, too fine granularity will make the simulation process more complicated and imperfect in ease of use. Therefore, proper granularity selection and hierarchical division is critical issue in the radar system simulation process. In this section, a five-layer radar system simulation framework is designed based on virtual reality technology, as shown in Figure 3.

4.1 System layer

The system layer is directly facing the application. Complete the construction of radar system simulation applications by customising and combining the required subsystems.

4.2 Subsystem layer

The subsystem layer can be divided into target scene subsystem, echo simulation subsystem, signal processing subsystem, data processing subsystem and display evaluation subsystem based on the working principle of

Fig. 3 Radar system simulation hierarchical framework based on virtual reality

classic radar system [10]. The target scene subsystem is used to simulate various types of target movement, beam irradiation, target rendezvous, target scattering simulation, etc. and generate corresponding target operating information as output. The echo simulation subsystem is mainly used to generate simulated target echo according to the given target operating information, superimpose interference signals such as simulated noise and clutter on it and output the echo signal after adding interference. The signal processing subsystem takes the echo simulation subsystem as input to complete some conventional signal processing, such as pulse compression (PC), moving target display (MTI), moving target detection (MTD), constant false alarm processing (CFAR), etc. The data processing system results from signal processing or externally given relevant target detection data as input and performs track generation, tracking and filtering on the target detection result. Finally, the display evaluation subsystem is mainly used to display exciting signals, data or graphics generated in the system. At the same time, evaluate the relevant performance of the radar system by calculating indicators such as the maximum detection distance and false alarm probability. The simulation block diagram of the subsystem level subsystem is shown in Figure 4.

Fig. 4 System layer simulation block diagram

4.3 Business role layer

The business role layer consists of various business roles that complete specific business functions in the upper subsystem, including role objects that complete actual business functions such as target operation roles, target echo roles, pulse pressure roles and trajectory filtering roles [11]. All radar simulation roles in this layer are implemented in a rule-oriented manner. Generally, a composite business role is constructed from multiple atomic business roles. The atomic role is generally constructed by different essential algorithm roles in the algorithm role layer below.

5 Simulation results

Many spectrum models used in radar clutter simulation are Gaussian or approximately Gaussian. The article takes the Gaussian frequency spectrum to illustrate the simulation method of related non-Gaussian distributed radar clutter. For the Gaussian spectrum correlation model, the specific form can generally be defined by the spectrum width between two half-power points.

$$S(f) = \exp\{-a[(f - f_0)/f_{3dB}]^2\} \quad (5)$$

f_0 is the maximum point position of the spectrum. In the actual simulation, we let $f_0 = 0$, f_{3dB} the width between the two half-power points. a is a constant, and its value should be $S(f_{3dB}/2) = 0.5$. Therefore, $a = 2\ln 2 = 1.665$ can be calculated from Eq. (5).

We can generate arbitrarily distributed correlation cluster sequences by using the method described above. The article simulates the clutter with the Gaussian spectrum. The article sets $f_{3dB} = 40\text{Hz}$ the number of sampling points $N=512$, and the sampling frequency is $(5f_{3dB}/N) = 200/N$. The specific results are shown in Figures 5–8.

Fig. 5 Random sequence PSD. PSD, power spectral density.

Figure 5 shows the power spectrum characteristics power spectral density (PSD) (dotted line) and the corresponding ideal spectrum characteristics of the relevant clutter output from the AR filter. It can be seen that within the half-power point range, the simulated clutter power spectrum characteristics are pretty consistent with the theoretical values. Figure 6(a), Figure 7(a) and Figure 8(a), respectively, show the Weibull distribution, lognormal distribution and K distribution clutter simulation sequence. Figure 6(b), Figure 7(b) and Figure 8(b), respectively, show the simulation results and theoretical results of the corresponding probability density.

Fig. 6 Simulation results of Weibull distribution clutter

Fig. 7 Simulation results of lognormal distribution clutter

Fig. 8 Simulation results of K-distributed clutter

6 Conclusion

Due to the continuous development of modern radar technology, accurate modelling and simulation of radar clutter have become more and more critical. It is a prerequisite for achieving optimal radar design. In this paper,

a radar clutter simulation system based on the ZMNL method is proposed, and various clutter distributions conforming to the Gaussian spectrum are simulated. The simulation results are in good agreement with the theoretical results, proving the feasibility of this system.

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