Research on Ultra-Wideband Radar Target Recognition Method

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Abstract. UWB (Ultra wide-band) radar, as a new system radar, has attracted more and more attention in military and civil fields such as target detection, imaging and recognition with its high range resolution, strong penetration, low interception rate and strong anti-interference. This paper focuses on the feature extraction methods based on pole distribution and scattering center combined with the characteristics and application directions of UWB radar. On this basis, combined with intelligent pattern recognition methods such as neural networks, fuzzy patterns, and information fusion, the problems that still need to be solved in the process of UWB radar target recognition are proposed.

1. Introduction

Radar, as an important electronic information equipment, has been greatly developed and used in the military and civil fields with its advantages of all-day, all-weather and long-distance[1]. It has gradually spread from the mature applications in the military field to the applications in the civil field. As a new detection technology, UWB radar has the advantages of high range resolution, strong penetration, low interception rate, and strong anti-interference, which makes it have great application value in the fields of target detection, imaging and recognition. So far, more and more scholars at home and abroad have actively explored and researched on UWB radar technology, and made some progress.

2. UWB radar Overview

2.1. Definition and composition of UWB radar

The concept of UWB radar was first proposed by the Los Alamos National Laboratory at the UWB Radar Conference held in March 1990. That is, when the ratio of the signal's bandwidth to the center frequency is greater than 25%, it is called an UWB signal.

The typical UWB radar consists of waveform generator, transmitter, receiver, transceiver antenna and signal processor[2]. Among them, the waveform generator generates the ultra-wideband signal waveform, which has one of the following two characteristics: having extremely short durations or complex waveforms (containing many frequency components)[3]. There are two kinds of UWB signal widely used: impulse signals and non-impulse signals. Among them, non-impulse signals are mainly LFM (linear frequency modulation) signals and random noise signals. Compared with the relatively simple impulse system UWB radar processing system, UWB LFM signals can be obtained without reducing the pulse width, but it is more difficult to satisfy the strict amplitude and phase requirements in each link (generation, transformation, amplification, etc.). The generation of random noise signals is

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relatively easy\cite{4}, which is an ideal ultra-wideband signal, but its application is limited due to the difficulty in receiving and matching processing.

2.2. The superiority of UWB radar

The large bandwidth of UWB radar means that more information and greater target detection probability can be obtained through signal spectrum analysis. Therefore, compared with traditional radar, UWB radar has many superior performances\cite{5}: high range resolution, strong penetrating ability, anti-interference ability, anti-stealth ability, target recognition ability, target imaging ability, and has better electromagnetic compatibility and frequency utilization.

2.3. Development and application of UWB radar

The United States, Russia and other countries have conducted long-term basic research and related applications of UWB radar technology, obtained a large amount of first-hand valuable data, which are at the leading level in the world. After entering the 1990s, UWB radar gradually became practical, such as the SRI system developed by the Stanford Research Institute of the United States, the BoomSAR developed by the U.S. ARL, the CARABAS developed by the Swedish Defense Research Military Organization, the P3 UHF UWB SAR system developed by the Michigan Institute of Environmental Studies, ARCHEO SAR developed by the Italian Archaeological Remote Sensing Project, and DERA UWB SAR developed by the Defense Evaluation and Research Agency, etc. These UWB radar systems utilize the large relative bandwidth and strong penetration characteristics of UWB signal for imaging and recognition of hidden targets.

China’s research on UWB radar started late, but research work is progressing rapidly. In 2000, the National University of Defense Technology first built an ultra-wideband orbital experimental SAR system\cite{6}. It successfully achieved the high-resolution imaging detection and identification of hidden targets of tree clusters for the first time in China, and it also confirmed the effectiveness of the system in the UHF/VHF band for leaf cluster penetration. In 2004, the National University of Defense Technology first developed the UWB Surface Penetrating Radar (SPR) system—RadarEye\cite{7} and hardware integrated software. The system can complete the evaluation of the road surface by realizing high-resolution road surface thickness estimation and the imaging of underground objects (including highway stratified detection, underground target 2D/3D imaging, underground target anomaly detection, underground target location and recognition and so on). With the deepening of research, UWB radar technology has also been successfully applied in emergency rescue, public safety, medical health and other fields\cite{8-10}. Van-Han Nguyen et al.\cite{11} developed an IR-UWB radar system, combined with KF (Kalman filter) method, signal compensation and false alarm elimination algorithm based on 2D jumping window, which effectively improve the target detection and tracking technology, reduce the number of false alarm, and compensate GPS and remote radar for errors in indoor positioning and rescue. Hao, Lv et al.\cite{12} used multi-static UWB radar and data fusion based on KF to solve the problem of human breathing detection with UWB radar. On this basis, Kim et al.\cite{13} proposed a 1D CNN (one-dimensional convolutional neural network) model that can classify and recognize five breathing patterns (Eupnea, Bradypnea, Tachypnea, Apnea, and Motion), with an average recognition rate of 93.9%, which is about 3%–13% higher than traditional methods (LDA, SVM and MLP).

3. UWB radar target recognition method

A radar recognition system model is shown in Figure 1, which consists of modules such as feature signal extraction, feature space transformation and classifier. Among them, the classifier needs the support of a feature database, and the target feature database is obtained from the training data through feature signal extraction and feature space transformation. Macroscopically, the radar target recognition process can be simplified into two main steps: feature extraction and classification decision.

Compared with the traditional radar system, UWB radar can simultaneously stimulate the scattering characteristics of the target’s resonance region, optical region and even the rayleigh region to obtain more abundant target and environmental information, thereby improving the accuracy of target
recognition. UWB radar target recognition methods can be divided into two types: model-based target recognition and model-free target recognition. Among them, model-based target recognition methods can be divided into two types: pole-based distribution and scattering center-based [5, 14].

3.1. Pole-based distribution method

According to the theory of Transient Electromagnetic Scattering, the transient response of a target can be divided into the impulse component (early-time response component) and the natural resonance component (late-time response component), and the target pole is the natural resonance frequency of the target. The target pole distribution depends only on the target shape and inherent characteristics. In other words, the target pole is the invariant of the excitation waveform frequency and the target posture [15], which is an ideal target recognition feature. Therefore, the target recognition method based on the pole feature has been a hotspot in the field of target recognition. There are two main research ideas of target recognition methods based on pole distribution:

The first method directly extracts the target pole as a feature from the radar echo, and completes the target recognition by matching with the feature database. The idea began with the Prony method proposed by Blaricum and Mittra in 1975, and then many scholars improved the Prony method, including the linear prediction method (KT method) proposed by Kumaresan and Tufts, and the matrix beam method [16] proposed by Sarkar et al. etc.

The second method indirectly utilizes waveform synthesis technique for target recognition. The most representative is E-pulse method proposed by Chen et al. in 1980, but this method requires the distortion-free transmission of the waveform. Subsequently, Chen et al. put forward an improvement scheme based on the methods of K-pulse and S-pulse: digitally convolving the received target scattered signal with the stored E-pulse representing the target, and if the convolution result is an expected zero output, the target to be identified is the corresponding known target. The method avoids extracting poles from the echo in real time, simplifies the calculation process, and also reduces the influence of noise when calculating the target pole. Since then, many scholars have verified the performance of the E/S pulse scheme, such as the E-pulse performance evaluation scheme developed by Mooney et al., the E-pulse development method based on β-spline [17] proposed by Blanco et al. and so on. In order to further improve the performance of E-pulse recognition under low SNR (signal-noise-ratio), Wang et al. proposed a new modified asymptotically unbiased E-pulse based method [18], in which the target echo is firstly cross-correlated and then filtered by E-pulse filter. And Wu et al. proposed a recognition method based on likelihood ratio test with pole characteristics (LRTPC) [19], which optimized the real-time performance of the recognition system and improved the recognition accuracy under low SNR.

3.2. Scattering center-based method

Unlike the pole feature, the scattering center feature of the target is related to the posture angle of target, and its properties and distribution reflect the surface geometry and other physical properties of the target, such as edges and tips. Therefore, the scattering center feature that can be observed under different attitude angles of the same target vary greatly, which provides more detailed information for target recognition. In addition, in the process of radar target recognition, there is no obvious boundary between early-time response and late-time response, and the pole-based target recognition method must accurately intercept the corresponding late-time response, so the pole-based target recognition method has great limitations. However, the early-time response energy of target is usually larger than the late-time response, and the scattering center feature can be directly extracted from the target echo distance.
image, so the target recognition method based on the scattering center is widely concerned. There are two main ways to obtain the target scattering center:

The traditional Fourier-based processing, which first calculates the inverse discrete Fourier transform (IDFT) of the scattering data to obtain the estimated impulse response of the target, then locates the scatterer by determining the peak in the estimated impulse response. Since the estimated response is calculated from the frequency samples of the radar bandwidth “B”, the Fourier-based processing limits the range resolution to approximately $c/2B$.

The model-based processing, which begins with the use of a parametric model to describe the measured scattering behavior, and then estimates the parameters describing the scattering from the data. The range resolution of the method is not limited by bandwidth, but is limited by the parameter estimation error and the approximation of the specific model describing the actual scattering behavior.

As early as 1976, Altes proposed the Altes model for representing the early-time response of a target. In 1987, Hurst proposed a solution to the scattering center frequency domain based on Prony method, which is superior to traditional Fourier transform techniques in both resolution and dynamic range. However, as the relative bandwidth increases, the mismatch between the Prony model and the real target scattering behavior becomes more and more obvious. In 1995, Potter et al. proposed a scattering model based on GTD (geometrical theory of diffraction), derived the Cramer-Rao lower bound based on the model parameters, and showed that the fields scattered from canonical scattering centers have distinct frequency dependence under wideband/ultra-wideband incident waves. Subsequently, in order to solve the problem that the Prony method is sensitive to random noise and the number of scattering centers, Li et al. proposed an Altes model-based fitting scheme using the least square method and genetic algorithm to determine the time position and amplitude of the scattering center. In 2006, Su et al. proposed a GTD model-based method using matching pursuits and a likelihood-ratio test in the frequency domain (MPLRT-GTD)[20], and the result reveal the physical phenomenon that the main scattering mechanism exists in the ultra-wideband response of the target scattering center, but it still has the disadvantages of large amount of calculation and poor real-time performance. In 2019, Jiang et al. analyzed the electromagnetic scattering characteristics and echo signal characteristics of radar targets based on the GTD model and proposed a wide-band radar echo simulation method based on dechirp, which effectively reduce the computational complexity and the difficulty of engineering implementation[21].

There are defects in the target recognition method based on the above two characteristics, so combining the scattering characteristics of the optical region with the scattering characteristics of the resonance region will undoubtedly improve the ability of UWB radar target recognition.

4. Intelligent pattern recognition method

4.1. Fuzzy pattern recognition

The fuzzy pattern recognition technology is developed on the basis of fuzzy sets theory. It can convert the target features extracted by numerical transformation to be characterized by fuzzy sets and membership functions, and then determine the belonging relationship of the targets through fuzzy relations and fuzzy reasoning, so as to effectively solve the problem of information fuzzy and target feature distortion[22]. Such as Wang et al. combined genetic algorithm (GA)[23], fuzzy pattern recognition (FPR) and ultra-wideband target recognition (GA-FPR)[24]. On the basis of FPR, the principle of maximum membership is used to target classification and recognition, and the GA is used to obtain the optimal solution of the sub-membership function, and the forward communication and target recognition can be completed simultaneously without special sensors.

4.2. Neural network recognition

Artificial neural network (ANN) is a network system that mimics the information processing mechanism of the human brain, which is made up of a large number of simple artificial neurons that are widely linked. It has strong self-learning, self-organization, parallelism, fault tolerance, and strong nonlinear adaptive processing capabilities, which can overcome the traditional artificial intelligence methods for
intuitions defects such as patterns, speech recognition, and unstructured information processing. Moreover, it can deal with some problems such as inconspicuous target features or unclear backgrounds by establishing memory on the learning of samples without establishing a physical model of the system. In the process of target recognition, ANN are often combined with technologies such as fuzzy sets, evidence theory, expert systems, genetic algorithms, and wavelet analysis. Such as neural network B-P algorithm,[25] improved B-P learning algorithm (MB-P), self-organizing feature mapping algorithm combined with wavelet analysis, fuzzy self-organizing neural network algorithm, CMNet network algorithms based on convolutional neural networks, which have been successfully applied in UWB radar target recognition.

In recent years, as an extension of neural networks, the deep learning method has attracted the attention of researchers in the field of radar target recognition[26]. For example, Feng et al.[27] used a stack correction autoencoder to perform radar automatic target recognition based on high-resolution range profiles. Chen et al.[28] successfully applied the improved deep convolutional neural network to SAR image target classification, and improved the accuracy of target recognition under the limited training set. Hu et al.[29] proposed the CMNet network model, which solved the problems of low recognition rate and insufficient generalization ability of SAR image target recognition algorithm.

4.3. Information fusion recognition
The information fusion algorithm comprehensively utilizes the performance advantages of various sensors, and has the advantages of improving the robustness and reliability of automatic target recognition systems, reducing the uncertainty of target recognition, and improving the accuracy of target recognition[14, 30]. Fusion recognition is divided into data-level, feature-level and decision-level fusion recognition. The advantages of the data-level fusion recognition are less information loss, but the disadvantages are that the algorithm is complicated, the calculation is large, and the requirements for communication are high, which is difficult to implement in real time. The advantage of the decision-level fusion recognition is that the communication requirement is relatively low, the algorithm is relatively simple and easy to implement, but the information loss is large. While the feature-level target fusion recognition can consider both performance and complexity, and can achieve considerable information compression, which is beneficial to real-time processing. At present, information fusion is combined with deep learning theory for unmanned obstacle recognition[31], and combined with fuzzy neural networks to improve the processing speed and accuracy of radar systems[32].

5. Conclusion
At present, there are still some difficulties in UWB radar target recognition. Firstly, in the process of target echo extraction, in addition to noise interference, there are also a lot of electromagnetic interference and complex background clutter. Secondly, the accuracy of the recognition results obtained by the current classification recognition algorithm is not ideal.

In recent years, although deep learning-based recognition research is a hot research direction, the training of deep neural networks requires a large number of samples. So the shortage of sample size at this stage has become a major factor restricting the application of deep learning in radar target recognition[33]. Therefore, we need to make comprehensive use of multiple feature extraction methods and intelligent pattern classification methods to achieve a better recognition. At the same time, with the development and application of modern signal processing technology and artificial intelligence technology, UWB radar target recognition will eventually become intelligent and practical.

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