A Novel Method of Radar Antenna Scan Pattern Recognition Using Visibility Graph

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Abstract. Radar antenna scan has a great influence on reconnaissance targets, interference decision-making, and electronic support measures. In this paper, we propose a recognition method of antenna scan pattern based on visibility graph, including circular scan, sector scan, helical scan, raster scan, conical scan, phased array scan, phased array azimuth scan and circular elevation scan. We have mapped the radar scans pattern, the azimuth and elevation curves of various scan patterns and the signal variation of the EW receiver. Moreover, the related features are extracted from the visibility graph and the seven radar scan patterns are classified by five kinds of classifiers. Simulation experiments verify the efficiency of the algorithm.

1. Introduction

Electronic countermeasures reconnaissance[1] is the utilizing of certain technical means to intercept, measure, analyze, identify enemy information systems and electronic signals. The aim is to obtain their technical parameters, functions, types, applications and so on. Electronic countermeasures reconnaissance is an important means of acquiring strategic tactical electromagnetic information and electronic warfare intelligence. It is the basis and premise for the implementation of electronic attacks and electronic protection and provides commanders with timely battlefield posture.

Radar working modes are generally divided into search, interception, tracking, shooting, guidance, fusion etc. [2]. The radar working mode information can be obtained through the beam of the radar antenna, then ECM, electronic support and electronic protection of the reconnaissance side can perform corresponding measures according to the detected information. Therefore, how to accurately obtain radar beam information through the EW Receiver is strongly critical [3-7].

In [3], algorithm for antenna scan type (AST) recognition in electronic warfare (EW) has been proposed. The stages of the algorithm are scan period estimation, preprocessing (normalization, resampling, averaging), feature extraction, and classification. Naive Bayes (NB), decision-tree (DT), artificial neural network (ANN), and support vector machine (SVM) classifiers are used to classify five different ASTs in simulation and real experiments. Classifiers are compared based on their accuracy, noise robustness, and computational complexity. In [4], the authors propose a new method based on correlation is proposed to determine the main beam signal. The proposed method gives better performance than amplitude thresholding-based algorithms for not only newly added but also other scan types. Also, main beam flatness ratio is proposed as a new feature to separate electronic scan types from
the other scan types. Intensive simulations are executed to evaluate the performance of the proposed new method and feature.

This paper proposes a method to combine visibility graph with machine learning[14], neural network and deep learning [15], and apply them to radar antenna scan pattern. Machine learning spans multiple disciplines such as computer science, engineering, statistics etc. In simple terms machine learning is the conversion of unordered data into useful information. The neural network is an information processing model similar to the human nervous system. It can change its structure according to external information model the direct weight of neurons and finally have the ability to solve problems. Deep learning is one of the branches of machine learning and one of the most promising directions in the field of artificial intelligence. Deep learning is a combination of multiple layers of nonlinear transformations resulting in a more abstract and more efficient representation of features.

In this paper, we simulate the signal observed by the EW receiver as a signal contaminated by additive random noise which is consistent with the existing literature [3-4]. However, it is more practical to add some measures to the model to resolve clutter and other structured noise. While taking into account signal aliasing, this is naturally an interesting topic and need to properly attention, but it is beyond the scope of this article and we will implement it in future work.

The rest of this paper is organized as follows. Section II provides the signal acceptance model of various radar antenna scan pattern. The basic visibility graph method proposed in this paper are overviewed in section III. Section IV briefly describe the feature extraction of the radar received signal by studying the visibility graph. Section V is the validate of this paper including simulation experiment setup experimental, results and conclusion.

2. Signal model
There are many patterns of radar antenna scan depending on the radar working mode, radar type and operating mode, etc. Radar antenna simulation can receive the periodicity and quantity of the radar signal, and provide theoretical basis for identifying the working mode of the radar and subsequent ES, EP, EA etc. The radar antenna scan pattern can be varied, but the EW receiver is generally an omnidirectional receiver, so the radar signal considered in this paper can be detected by the EW receiver. Here are seven radar scan patterns as follows.

2.1 circular scan
As shown in Fig. 1(a), circular scan is widely used for search radars. The antenna scans 360° in the azimuth at a constant rate, while elevation angle is kept fixed. Typically, the antenna beam is wide in the elevation axis to cover the region of interest and narrow in the azimuth axis to provide good resolution. This type of beam is called fan beam. Such a radar is expected to provide range and azimuth information but not elevation. Depending on the requirements of maximum detection range and integration time, scan period may vary between 5 and 30 s [8, 10].

2.2 circular scan
In the sector scan, the radar sweeps a specific angular sector back and forth at constant angular speed. The EW antenna receives periodic and symmetric main beams, as shown in Fig. 1(b). Two main beams with equal peaks are expected for each full period. The ASP is on the order of seconds.

2.3 Conical scan
The conical scan pattern is generally used for target tracking [4], and the amplitude of the signal received is considerably related to the position of the EW receiver [2] as shown in Fig. 1(c). When the radar scan pattern is conical scan and the EW receiver is on the circle, the amplitude of the signal received is similar to the circular scan which is a sinusoidal waveform with the largest amplitude; if the EW receiver position is within the circle except the center of the circle, at this time it is also a sinusoidal waveform but the signal amplitude is limited by the radius; when the EW receiver is at the
center of the circle, the distance from the radar to the EW receiver is fixed, therefore the signal amplitude is fixed [3]. The spiral scan is similar to the conical scan except that the rotation angle of the vertebral body itself can be changed. The amplitude of the signal is still sinusoidal but it is limited by the direct angle of the beam and position of the receiver. This paper will not be described here. Readers can read the literature [3].

2.4 Helical scan
Helical scan is normally used in search states. Helical scan azimuth is omnidirectional and the azimuth angle is changed after each scan. The helical scan analysis is shown in Fig. 1(d). Therefore, the helical scan pattern includes not only azimuth orientation information but also elevation angle information. A higher scan frequency can be used during the helical scan process which can decrease the gap generated in the search.

2.5 Raster scan
The two scan types described above search only in azimuth, but the raster scan searches both in azimuth and elevation. The two scan types described above search only in azimuth, but the raster scan searches both in azimuth and elevation. The period is constant and in each full period, a main beam is intercepted for each bar of the raster scan. However, since the elevation is also changing in this scan type, the received PA varies with the elevation of the EW receiver.

2.6 Phased array scan
The phased array radar scan pattern is electronically scanned, and it can be randomly changed from one direction to the other by control. One-dimensional phase scanning radar adopts the electrical scanning mode in the pitching direction and mechanical scanning mode in the azimuth direction, while AESA radar employs electric scanning mode in both of the pitch and azimuth direction. So, we can model the antenna pattern and working pattern of the three radar systems to prepare for the calculation of the feature parameter. In this paper, the beam dwell time is set to 0.1s and the relationship between the received power and time of the phased array scan EW receiver is shown in Fig. 1(f).

2.7 Phased array azimuth scan and circular elevation scan
The combination of phased array azimuth scan and circular azimuth scan is generally used for target search, tracking and measurement mission. As shown in Fig. 1(g), compared with mechanical scan radar, this pattern is more flexible, it can track more targets and has better anti-interference performance. Moreover, it can also find invisible targets.

Fig1. (h) is shown the geometric relationship between radar and EW receiver position. This is a phased array radar scan pattern. The EW receiver is fixed in position and passively receives the signal amplitude of the radar.
3. Introduction to the visibility graph

In [12], a method for converting a time series into a visibility graph has been intensively proposed. It can be summarized as if there is a straight line connecting the data as long as the line does not intersect any intermediate data. Suppose there are three sets of points whose corresponding coordinates are $(t_1, y_1), (t_2, y_2), (t_3, y_3)$. If they have visibility for any of points 1 and 2, they can be connected to two nodes of the associated graph. If point 3 is between them, then they meet the following conditions

$$y_1 < y_3 + (y_1 - y_2) \frac{t_3 - t_1}{t_2 - t_1}$$

And there are three principles between them

1. Connectivity: Each node sees at least its nearest neighbors (left and right).
2. Undirected: the way the algorithm is built up, there is no direction defined in the links.
3. Invariant under affine transformations of the series data: the visibility criterion is invariant under rescaling of both horizontal and vertical axes, and under horizontal and vertical translations. Fig. 2(a) shows the connection diagram of time series conversion to visibility graph, simpler as shown in Fig. 2(b). See [20] for details.
Fig. 2. An example of a visibility graph algorithm. (a) Each node is connected to the line data and (b) the corresponding point is converted into a connection point of the graph theory algorithm.

4. Feature extraction
Fig 3 is a flow chart of the design algorithm of this paper. Firstly the relevant amplitude information is received by scanning pattern, then the relevant parameters of the EW receiver are set, next the viewable model is constructed and the signal model is converted into a visibility graph complex network. Then we perform feature extraction from the complex network. Finally, we use five classifiers to perform the recognition operation.

The visibility graph relevant theory is introduced above and its application has penetrated into various fields. Using the VG approach, we can obtain a graph that has special topological properties. It allows us to use the complex graph approach to analyze the vibration signals. Fortunately, the features or properties of the complex graph have been discussed in previous studies. The features to measure the hidden information in the graph include graph density, degree distribution, average path length, the clustering coefficient, etc.

EW receiver detects radar signal amplitude signal
Set EW receiver model parameters and detection parameters
Construct the visibility graph model
Send the EW receiver detection model to the visibility graph and build the complex network
Feature extraction of the constructed complex network
Classification and identification of features by each classifier

Fig. 3 Radar antenna scan pattern recognition flow chart

(a)

(b)
4.1 Average degree
The first feature we select is the average degree, it is one of the most intuitive and convincing features. It can be expressed as
\[ \bar{d} = \frac{1}{N} \sum_{i=1}^{N} d_i \]  

(2)

4.2 Average clustering coefficient
The concept of average clustering coefficients first proposed in [9]. The definition of average clustering coefficients can be expressed as
\[ C_i = \frac{(A_i^2)_{ii}}{(A^2)_{ii}} \frac{1}{(A^2)_{ii} - 1} \bar{C} = \frac{1}{N} \sum_{i=1}^{N} C_i \]  

(3)

4.3 Newman Coordination Coefficient
Literature [10] proposes a hybrid network model, defined as a network that exhibits a cooperative mix if nodes with many connections in the network tend to connect to other nodes with many connections. In the simplest case, a network is represented by an undirected graph of N vertices and M edges which can be written as
\[ r = \frac{M^+ \sum_{i,j} d_i d_j - \left[ M^+ \sum_{i,j} \frac{1}{2} (d_i + d_j) \right]^2}{M^+ \sum_{i,j} \frac{1}{2} (d_i + d_j) - \left[ M^+ \sum_{i,j} \frac{1}{2} (d_i + d_j) \right]} \]  

(4)

4.4 Normalized network structure entropy
For the purpose of eliminating the influence of the number of vertices N on the entropy E of the network structure, we introduce the concept of normalized network structure entropy which can be written as
\[ E_{\text{norm}} = \frac{E - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}} = \frac{-2 \sum_{i=1}^{N} I_i \ln I_i - \ln 4(N-1)}{2 \ln N - \ln 4(N-1)} \]  

(5)

4.5 Visibility graph complexity
The eigenvalues of all neighbor matrices of the VG graph are real numbers, and the largest one is recorded as \( r_{\text{max}} \). Then we are easy to know \( 2 \cos(\pi/(N+1)) \leq r_{\text{max}} \leq N-1 \), so that the visibility graph complexity can be constructed as [11]
\[ C_r = 4c_r (1-c_r), c_r = \frac{r_{\text{max}} - 2 \cos \frac{\pi}{N+1}}{N-1 - 2 \cos \frac{\pi}{N+1}} \]  

(6)

4.6 Visibility graph density
The visibility graph density can directly reflect the size of the graph, and the visibility graph density can be represented by a visibility graph neighbor matrix. It can be expressed as
\[ G_d = \frac{\sum_{i,j} m_{i,j}}{N(N-1)} \]  

(7)

5. Experimental results and Conclusion
In this section, according to the VG features described in Chapter VI, the classifier is used to classify and identify the VG features. The features were classified in the experiment using the five classifiers described above. We compare the performance of the visibility graph algorithm proposed with the
recent algorithm [3] [7], and introduce a large number of Monte Carlo simulation experiments. Finally this paper present a summary of the perspective.

Fig. 4 Performance of each classifier under different SNR

The first experiment is the direct comparison of each classifier. They are SVM, BP neural network, naive Bayes, MLP, DBN, which are classified by the features that can be extracted by visibility graph. In this experiment, we divide the SNR into 0-10dB and the performance of each classifier is shown in Fig. 4.

The second experiment is compared with the recent literature [3][7]. The classifier methods considered are NB, ANN and SVM and the experimental conditions are all in the same environment. Fig. 5 shows a comparative experiment with the literature [3]. It suggests the superiority of the proposed algorithm and robustness to noise.

Fig. 5 Comparison of simulation performance with literature [3]. (a) NB (b) ANN (c) SVM

Fig. 6 Performance of each classifier under different SNR
Fig. 6 shows a comparison of successful recognition probabilities with literature [7] at different SNR. Obviously, the algorithm proposed in this paper shows not only very good performance but also robust to noise. This is inseparable from the superiority and feature selection of the visibility graph algorithm. Therefore, we reasonably believe that the proposed algorithm has a certain degree of effective understanding of the radar antenna scanning method.

The hyperparameters of the proposed algorithm has been determined to guarantee the maximum performance based on various simulations, and the proposed algorithm has demonstrated with numerous Monte Carlo simulations that it achieves a superior performance than the recent radar antenna scan pattern introduced in the literature. The average recognition probability was generally greater than 90% when the SNR was greater than 4dB. The classification performance was strongly excellent, and the simulation experiment demonstrated the effectiveness of the algorithm.

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