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Research on the Design of Signal Processing Algorithm Scheme for Vehicle-mounted Millimeter-wave Radar

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ABSTRACT

Among the common vehicle-mounted radars, vehicle-mounted millimeter-wave radar is an important component of vehicle-mounted sensors. The core of the vehicle-mounted millimeter-wave radar system is its signal processing module. Signal processing algorithms based on digital signal processing technology have extremely important and far-reaching significance for the research and development of vehicle-mounted millimeter-wave radar. This paper analyzes the overall structure and basic working principle of the vehicle-mounted millimeter-wave radar system, designs a signal processing algorithm structure scheme of "Beat - Beamforming - Fourier spectrum analysis -MTD", and studies three key algorithms involved in FMCW radar signal processing: CFAR detection, MTD technology, and MTD velocity pairing method.

KEYWORDS

Millimeter-wave Radar; Signal Processing; FMCW Radar Signal Processing; CFAR Detection; MTD Technology.

1. INTRODUCTION

In recent years, with the vigorous development of automobiles in the directions of intelligence and electrification, autonomous driving has gradually become a research hotspot in global technology. The emergence of autonomous driving technology in automobiles marks a revolution in the field of intelligent transportation. Autonomous driving has become an inevitable trend in the future development of the automotive industry. The introduction of autonomous driving technology has brought many advantages to modern transportation, such as improving traffic safety, alleviating traffic congestion, and enhancing driving and riding comfort. The key technologies of autonomous driving include four major parts: environmental perception, behavior decision-making, path planning, and motion control. Among them, environmental perception, as the first step in the autonomous driving process, is the basis for the interaction between the autonomous driving system and the outside world. The perception effect will greatly affect the decision-making and planning processes, and thus impact the safety of autonomous driving. Therefore, improving the accuracy of environmental perception is the key to enhancing the performance of autonomous driving systems. The four major sensors of autonomous vehicles, namely cameras, lidar, ultrasonic radar, and millimeter-wave radar, are equivalent to human senses and can make judgments based on the external environment. Due to its all-weather and all-time capabilities, high precision, small size, and high cost-effectiveness, millimeter-wave radar has become a mainstream solution for accurate perception and positioning in environmental monitoring sensors and is also an important factor in improving the level of automotive driving automation.

1.1. Classification of Millimeter Wave Radar

Millimeter wave radar is a kind of radar that operates in the millimeter wave band detection, which operates at a wavelength of 1 to 10 mm and a frequency range of 30 to 300 GHz. The electromagnetic wave in this frequency band can form a narrower and better directional beam, which can improve the resolution of the radar to the target. At present, the automotive millimeter wave radar, which is widely used in the field of traffic monitoring and automatic driving, can be divided into 24, 77, 79 GHz according to the frequency, and can be divided into short-range radar, which can be divided into 24, 77, 79 GHZ according to the detection range. SRR), medium-range radar (MRR), and long-range radar (LRR), as shown in Figure 1.

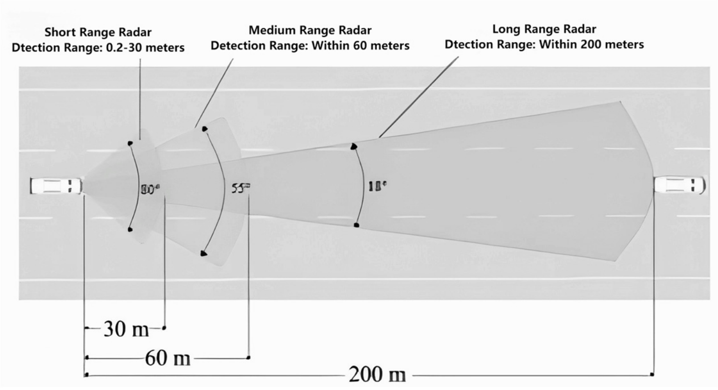

Fig 1. The classification and range of automobile millimeter wave radar

Automotive millimeter-wave radars have different detection ranges and frequencies depending on the type. SRR has a detection range of 0.2 to 30 meters and a frequency of 24 GHz. The MRR has a detection range of up to 60 meters and a frequency of 77 GHz. The LRR has a detection range of up to 200 meters and a frequency of 79 GHz. Higher frequency results in higher detection range and resolution, but also larger volume and antenna size. Automotive millimeter-wave radar is divided into forward and angular radar. The forward radar has a detection range of 200 meters, a field of view angle of ±45°, and is installed in the front of the vehicle. The angular radar has a detection range of about 70 m and a field of view angle of ±60 and is installed near the searchlights and taillights at the front and rear of the vehicle to detect blind spots. In addition, radar is divided into pulse and continuous wave type according to the mode of operation. At the same time, according to the different signal transmission mode, continuous wave radar can be divided into Constant Frequency Continuous Wave (CFCW), frequency-shift keying (FSK), and frequency modulated continuous wave (FMCW); CW can only obtain the target speed information, can not obtain other information about the target, FMCW can measure the speed and distance information of a single target or multiple targets at the same time. Therefore, FMCW is more suitable for application in the vehicle terminal.

2. FMCW RADAR

In the field of vehicle millimeter wave radar, linear frequency modulated continuous wave (FMCW) system is the most widely used. The vehicular FMCW millimeter wave radar consists of an RF front-end module and a signal processing module. The RF front-end module is responsible for adjusting the transmitted signal frequency and sending it, processing the received signal, and then passing it to the mixer. The mixer mixes the signals and filters them to produce an analog IF signal containing the target information. After power amplification, these signals are sent to the digital signal processing module for further processing. The digital signal processing module is responsible for generating the modulated waveform, converting the analog signal into a digital beat signal, and using the algorithm to calculate the distance, speed, and angle of the target.

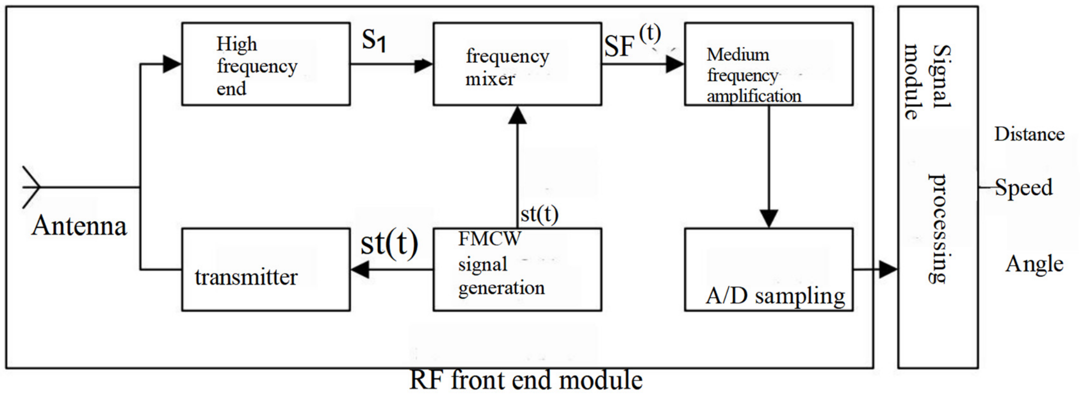

Fig 2. System diagram of FMCW millimeter wave radar

The specific system block diagram is shown in Figure 2. The local oscillator of the system is the transmitted signal with a small amount of energy, and the IF signal can be obtained by mixing with the target signal echo. Usually the transmitted signal has two kinds of Linear Frequency Modulation Continuous Wave (LFMCW) : sawtooth wave and triangle wave. The range and velocity of the target can be measured without ambiguity when using sawtooth wave, while the range and velocity of the target can be measured without ambiguity when using triangle wave with only one cycle of signal. The processing process is simple and easy to realize. The specific principle is to measure the range and velocity of the moving target according to the correlation and spectrum pairing of the frequency change of the transmitted signal and the echo signal. It is the most easy to implement range and velocity continuous wave radar. FMCW radar has the advantages of low transmitter power, high receiver sensitivity, easy to achieve extremely high range resolution, no range blind zone, simple structure and easy to implement. At the same time, there are two significant disadvantages. On the one hand, because the transmission and reception of FMCW radar are carried out at the same time, when the range is required to increase, the signal power also needs to be increased. This will indirectly lead to the receiver not working properly, because at this time the transmitter to the receiver leakage power will also increase, so the range of FMCW radar is limited. In addition , the resolution of a certain condition to increase the range of the sampling points will also increase linearly, so that the amount of FFT calculation in digital processing faster than linear law growth. Therefore, the action distance will be limited by the development of digital signal processing technology. On the other hand, when the LFM signal with large time-band product is used in the FMCW radar, The range-velocity coupling problem will appear from the radar signal ambiguity function theory, which not only leads to the decrease of the actual resolution ability of the system, but also produces the range error of the moving target. Therefore, specific signal processing techniques must be used to address or mitigate these two drawbacks. To solve these problems, the "beat-Fourier spectrum analysis-MTD" signal processing architecture is usually used in the vehicle millimeter wave radar. By spectral analysis of the beat signal, the target can be detected and its parameters such as range, velocity and angle can be estimated. At the same time, combined with Moving Target Detection (MTD) technology, the range-velocity coupling problem can be overcome and the pairing of multi-target information can be realized. In addition, the application of beamforming technology to FMCW vehicle millimeter wave radar can effectively suppress interference, clutter and noise, enhance the target signal, so as to improve the target detection performance in complex scenes with multiple targets, multiple interference, strong clutter and strong noise, and alleviate the problem of limited range of FMCW radar.

Vehicular millimeter wave radar uses FMCW system. The main algorithms include CFAR detection, multi-target pairing and beamforming, which are used for target detection and range, velocity and angle estimation. CFAR detection algorithm has formed a complete theoretical system, and is mature in engineering. It is a key link in radar signal processing. The proposed algorithm can adaptively adjust the detection threshold according to the clutter intensity and maintain a constant false alarm rate to maximize the detection probability. CFAR detection is usually performed in the time domain, but can also be performed in the frequency domain, which is called frequency domain CFAR detection. The off-beat signal is often transformed to the frequency domain in the signal processing of vehicle millimeter wave radar, so frequency domain CFAR algorithm is suitable for target detection.

3. MILLIMETER-WAVE RADAR SIGNAL PROCESSING ALGORITHM SCHEME

In the driving process of the vehicle, there will be many interference factors (such as guardrails, signs, trees, etc.) in the detection of the target by the vehicle millimeter wave radar, and there will be some system noise inside the radar. These interference conditions will affect the normal operation of the millimeter wave radar, reduce the detection performance of the radar for the target object, and it is easy to miss and false detection. It affects the safety of vehicle driving. In order to accurately identify the distance, speed and other information of the target, some signal processing algorithms can be used to filter the interference and clutter. It is necessary to study and design the signal processing algorithm of the vehicle millimeter wave radar.

3.1. Scheme of Signal Processing Algorithm for Millimeter Wave Radar

The traditional millimeter-wave radar signal processing scheme adopts the algorithm structure of "beat signal and Fourier transform" in the signal processing module, and the range and speed of the target can be calculated by measuring the upper and lower beat frequency according to the signal spectrum. However, this traditional signal processing algorithm does not solve the problem of low resolution and false alarm and miss alarm in the process of signal processing, so it is necessary to use a certain signal processing algorithm to filter out clutter. In order to improve the resolution, a CZT algorithm is proposed. For the problems of false alarm and missing alarm in traditional CFAR detection algorithm, an improved CFAR detection algorithm is proposed, and the feedback mechanism is introduced. In order to solve the problem that the velocity distance obtained by the up and down difference beat frequency is wrong when multiple target objects are detected, the LFMCW + CW multi-target pairing algorithm is introduced. Therefore, the signal processing algorithm scheme of "beat signal - time-frequency transform -CFAR- multi-target pairing" is proposed in this study. This is shown in Figure 3.

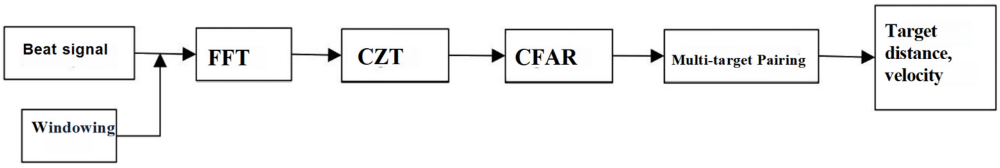

Fig 3. Signal processing scheme of millimeter wave Radar

In the whole signal processing process, the main algorithm modules are:

3.1.1. Beamforming Module

Beamforming includes receiving beamforming and transmitting beamforming. The main function of beamforming is to suppress interference, clutter and noise, enhance the target signal, and thus enhance the target detection rate. Since the spectrum characteristics of the beat signal including target range, velocity and Angle information are not changed after beamforming, the basic principles of target detection and target range, velocity and Angle estimation are similar to the principles under the "beat - Fourier spectrum analysis-MTD" signal processing structure.

3.1.2. FFT Module

FFT module, namely the digital signal sequence for the Fast Fourier Transform (Fast Fourier Transform, FFT), is a fast operation method of Discrete Fourier Transform (DFT). Through the FFT module, the time domain beat signal is transformed to the frequency domain for analysis, and the targets at different distances will be distributed in different frequency points, which is called "distance dimension transform". At the same time, the Fourier transform is also prepared for the subsequent frequency domain CFAR detection.

3.1.3. CFAR Detection Module

The CFAR detection module is mainly based on the principle of frequency domain CFAR detection, that is, the frequency domain signal after the time domain difference signal FFT, that is, "distance dimension transformation", calculates the detection statistics and threshold, and then makes a decision.

3.1.4. MTD (Multi-Target Pairing) Module

The MTD module mainly uses the fixed phase difference of the signals with different periods to obtain the Doppler frequency of the moving target, and then estimates the target velocity, which is called "velocity dimension transformation". At the same time, it also makes preparation for the subsequent multi-target pairing algorithm.

3.1.5. MTD-Speed Pairing Module

The MTD-velocity pairing module is mainly to solve the range-velocity coupling problem and make the distance information and velocity information of each target get an effective pairing.

3.2. Main Parameter Settings of the Algorithm

According to the principle of detection and range, speed and Angle estimation of the target vehicle discussed above, the main parameters of the signal processing algorithm for the FMCW vehicle millimeter wave radar at 24 GHz band in this study are set as follows:

3.2.1. Frequency Modulation Bandwidth B

For the determination of the frequency modulation bandwidth of the transmitted signal, the following factors are mainly considered: i. Avoid parasitic amplitude modulation. In the process of frequency modulation, the output signal of the oscillator has parasitic amplitude modulation, so that the mixer will output the signal of modulation frequency when no echo signal is received.

Therefore, the parameters need to be set within the range of the mixer beat frequency f_b *(or* the average beat frequency f_{bav}*) much* larger than the frequency of the modulated triangle wave f_m .

3.2.2. Reduce Fixed Error

Since the spectrum of the beat difference signal output by the mixer is discrete, its frequency can only be an integer multiple of the frequency of the modulated triangular wave, so it will cause a fixed error independent of the distance.

Let the modulation frequency be, respectively nf_m and $(n + 1) f_m$, then the fixed error is the difference between the corresponding distances of the two. When the detection distance is very long, the relative value of the fixed error is very small, and the impact on the accuracy of the detection is also very small. However, when the detection range is very close, the detection range is comparable to the interaction distance of the system target, and it is very possible to miss the target.

3.2.3. ADC Sampling Rate Limit.

According to the Nyquist sampling theorem, the sampling frequency should be at least twice the frequency of the highest signal to ensure that there is no aliasing.

3.3. Key Algorithms in FMCW Radar Signal Processing

3.3.1. CFAR Detection

CFAR detection is a process that adaptively changes the threshold value continuously according to the local noise energy information while keeping the false alarm probability constant in the clutter interference environment. For FMCW radar, the beat signal is transformed by FFT to frequency domain for CFAR processing. Here, the classical cell-averaged CFAR (CA-CFAR) algorithm is selected, and the specific detector structure is shown in figure. 4. Suppose the signal amplitude is A, the Doppler frequency is f_{d}, the initial phase is 0, then its complex envelope sample sequence is

$$x_{\mathrm{s}}[n] = Ae^{-j(2\pi f_{\mathrm{d}} nT_{\mathrm{r}} + \phi_0)} (n = 0,1,\cdots N_{\mathrm{s}} - 1)$$

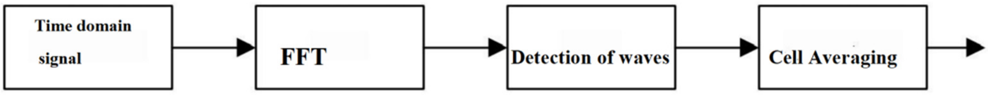

Fig 4. CA-CFAR detection structure in frequency domain

Since the frequency shift of the signal in each channel is not the same, the frequency shift in the k_{d} branch is $k_{\mathrm{d}} / N_{\mathrm{s}} T_{\mathrm{r}}$, and T_{r} is the signal repetition period, so it is obtained after FFT transformation.

$$X_{\mathrm{s}}(k_{\mathrm{d}}) = k_{\mathrm{d}} Ae^{-j\phi_0}$$

Since N_{s} point FFT is equivalent to N_{s} path coherent integrator, when $f_{\mathrm{d}} = k_{\mathrm{d}} / N_{\mathrm{s}} T_{\mathrm{r}}$,that is, the signal is matched with the coherent integrator, then | Xs (k_{d}) | is maximum in N_{s}sample values; when $f_{\mathrm{d}} \neq \mathrm{kd}$ / NsTr, that is, the signal does not match the coherent integrator, that is, | Xs (k_{d}) | decreases, which reflects the frequency selectivity of FFT.

Same as CA-CFAR in time domain, the algorithm principle of CFAR in frequency domain is shown in FIG. 5. When the time domain difference signal is performed FFT, that is, "distance dimension transformation", the range spectrum P_z detected in each distance dimension is used as the detection statistics. The adjacent range spectral line before and after it is taken as the reference unit, and the protection unit is reserved before and after the spectrum line to be detected according to the specific situation. In the detection process, the detection threshold P_j is obtained by calculating the average value P_j of the reference cell in the "sliding window" and multiplying by the threshold coefficient, where the threshold coefficient is

$$\alpha = N_{\mathrm{win}} \left(\frac{1}{(P_{\mathrm{fa}})^{N_{\mathrm{win}}}} - 1 \right)$$

That is, the threshold coefficient is determined by the length of the constant false alarm probability P_{fa} and the length of the "sliding window" N_{win}. In practice, it can also be adjusted by debugging the system program.

By comparing the detection statistic P_z with the detection threshold P_j, if $P_z > P_j$, the target is detected, otherwise, the target is not detected. The specific frequency domain CA-CFAR detection process is shown in Fig. 6.

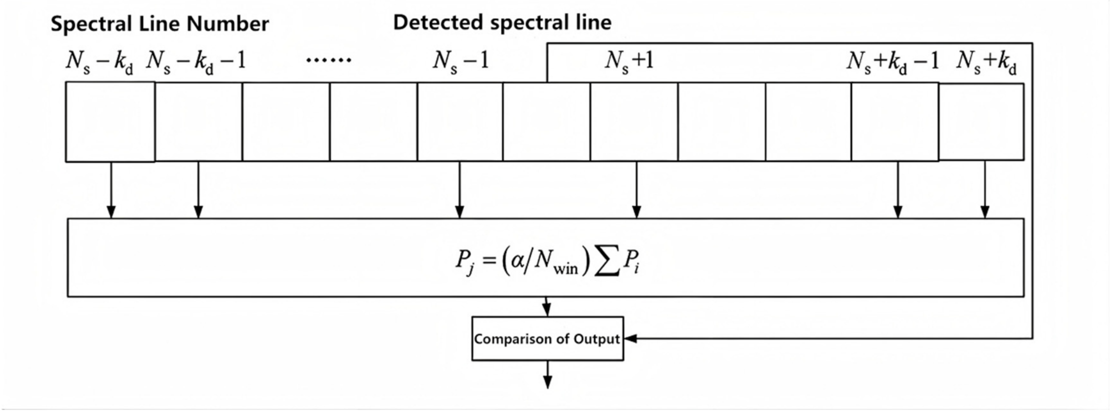

Fig 5. Schematic diagram of CA-CFAR algorithm in frequency domain

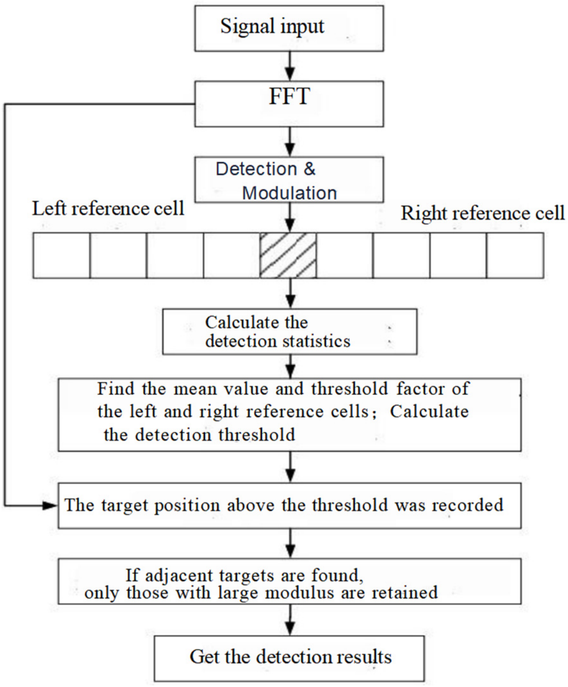

Fig 6. Flow chart of CA-CFAR in frequency domain

It is worth noting that when calculating the detection statistics, if the detected spectral line is in the edge position, that is, the number of adjacent spectral lines before and after it is not enough for the reference unit number, the spectral line of the reference unit number can be taken on a separate side to calculate the average value. In practice, the targets detected by CFAR often correspond to continuous multiple spectral lines, which is caused by various reasons such as spectrum leakage processed by FFT or the limitation of radar resolution. In order to eliminate its influence, three spectral lines can be usually selected as a unit according to the main lobe width after FFT processing. If the middle spectral line is larger than the amplitude of the left and right sides of the spectral line, it will be retained, otherwise it will be removed and re-screened.

3.3.2. MTD Technology

MTD technology can be used to achieve radar clutter suppression and target detection in millimeter wave radar signal processing. According to the previous analysis of FMCW signal, the beat signal is modulated by the Doppler frequency f_d, and the real part of the beat spectrum changes with the period number of the signal and shows a cosine envelope. Through MTD processing, the dynamic clutter can be suppressed, and the moving targets with different speeds can be distinguished according to the fuzzy Doppler frequency.

Considering the difficulty of practical engineering implementation and filtering performance, "MTI+FFT" is a common way to realize MTD technology. Specifically, the processing is divided into two steps: firstly, MTI filtering is carried out to suppress ground clutter; Then the Discrete Fourier Transform (DFT) is applied. As a fast algorithm of DFT, Fast Fourier Transform (FFT) has much less computation than DFT, so FFT is chosen to realize it.

In addition, MTD technology divides different targets into multiple velocity channels according to the Doppler frequency corresponding to the velocity in the velocity dimension. Based on this, the pairing of multi-target detection can be carried out to solve the problem of range-velocity coupling. Therefore, the MTD technology can be used to solve the problem of FMCW radar in complex environment, which cannot be solved by the frequency domain pairing method alone. In addition, considering that in the actual work process, MTI processing is not needed, because the information of the fixed target should be retained, so this paper directly implements MTD through FFT of the velocity dimension to suppress the dynamic clutter interference. Therefore, the FFT of the beat signal is performed twice, that is, "distance dimension transformation" and "velocity dimension transformation" (or "MTD transformation"), and the range spectrum and velocity spectrum are obtained accordingly.

3.3.3. MTD-velocity Pairing Method

In the signal processing process of FMCW radar, after two FFT, the signal spectrum peak appears at f_{R} and fuzzy Doppler frequency $\bar{f}_d = f_{\mathrm{d}} \bmod f_{\mathrm{r}}$, where $f_{\mathrm{r}}=1/T_{\mathrm{r}}$, mod$(\cdot)$ represents the remainder operation. The specific idea of MTD-velocity pairing method is: the "distance dimension transformation" is carried out on the beat signals of the upper and lower scanning bands respectively, and the upper and lower beat frequenciesf_{R}^{+}, f_{R}^{-} are obtained, and the target speed is obtained. Then, the computed fuzzy velocity of the target was obtained by computing the remainder of the computed target velocity with respect to the $\bar{V}_{\max}$ (maximum unambiguous velocity max). The identity of the target was judged by comparing the computed fuzzy velocity of the target with the measured fuzzy velocity of MTD. That is, after performing two-dimensional FFT operation on the difference beat signals of the periodic upper and lower scanning frequency bands, the number of targets in the upper and lower scanning frequency bands can be determined as N^{+} & N^{-} respectively, and the target distance frequency in the upper and lower scanning frequency bands can be determined as $F_{\mathrm{R}}^{+}=[f_{\mathrm{R}}^{+}{}_{,1}\ f_{\mathrm{R}}^{+}{}_{,2}\cdots f_{\mathrm{R}}^{+}{}_{\mathrm{N+}}]$ &$[f_{\mathrm{R}}^{-}{}_{,1}\ f_{\mathrm{R}}^{-}{}_{,2}\cdots f_{\mathrm{R}}^{-}{}_{\mathrm{N}^{-}}]$, and upper and lower scanning fuzzy doppler frequency spectrum $F_{d}^{+}=[f_{d}^{+}{}_{,1}\ f_{\mathrm{d}}^{+}{}_{,2}\cdots f_{\mathrm{d}}^{+}{}_{\mathrm{N+}}]$ &$[f_{\mathrm{d}}^{-}{}_{,1}\ f_{\mathrm{d}}^{-}{}_{,2}\cdots f_{\mathrm{d}}^{-}{}_{\mathrm{N}^{-}}]$, Then the flow of MTD-velocity pairing algorithm is shown in Fig. 7.

In FMCW system vehicle millimeter wave radar, on the basis of "beat - Fourier spectrum analysis-MTD", introducing the beamforming technology, the signal processing algorithm scheme under the "beat - beamforming - Fourier spectrum analysis-MTD" signal processing structure is studied, as well as the basic principle of the algorithm and the main parameter settings. Since beamforming does not change the frequency characteristics of the beat signal spectrum, the basic principles of the target detection and target range, velocity and angle estimation algorithms are similar to the algorithms under the "beat - Fourier spectrum analysis -MTD" signal processing structure.

4. SUMMARY

This study starts with the classification of millimeter wave radar, introduces its application scenarios, and carries out research on the signal processing algorithm scheme of the vehicle millimeter wave radar. Taking the vehicle millimeter wave radar of FMCW system as the research object, the overall scheme design of the algorithm under the signal processing structure of "beat - beamforming - Fourier spectrum analysis -MTD" is constructed. The basic algorithm principle is discussed. And the key algorithm modules involved in the whole signal processing process are studied, including MTD technology, CFAR detection, MTD-velocity pairing. The millimeter radar system based on FMCW system is simple and easy to realize, and has the advantages of low transmitter power and high receiver sensitivity, easy to achieve high range resolution, no range blind zone, simple structure and easy to realize.

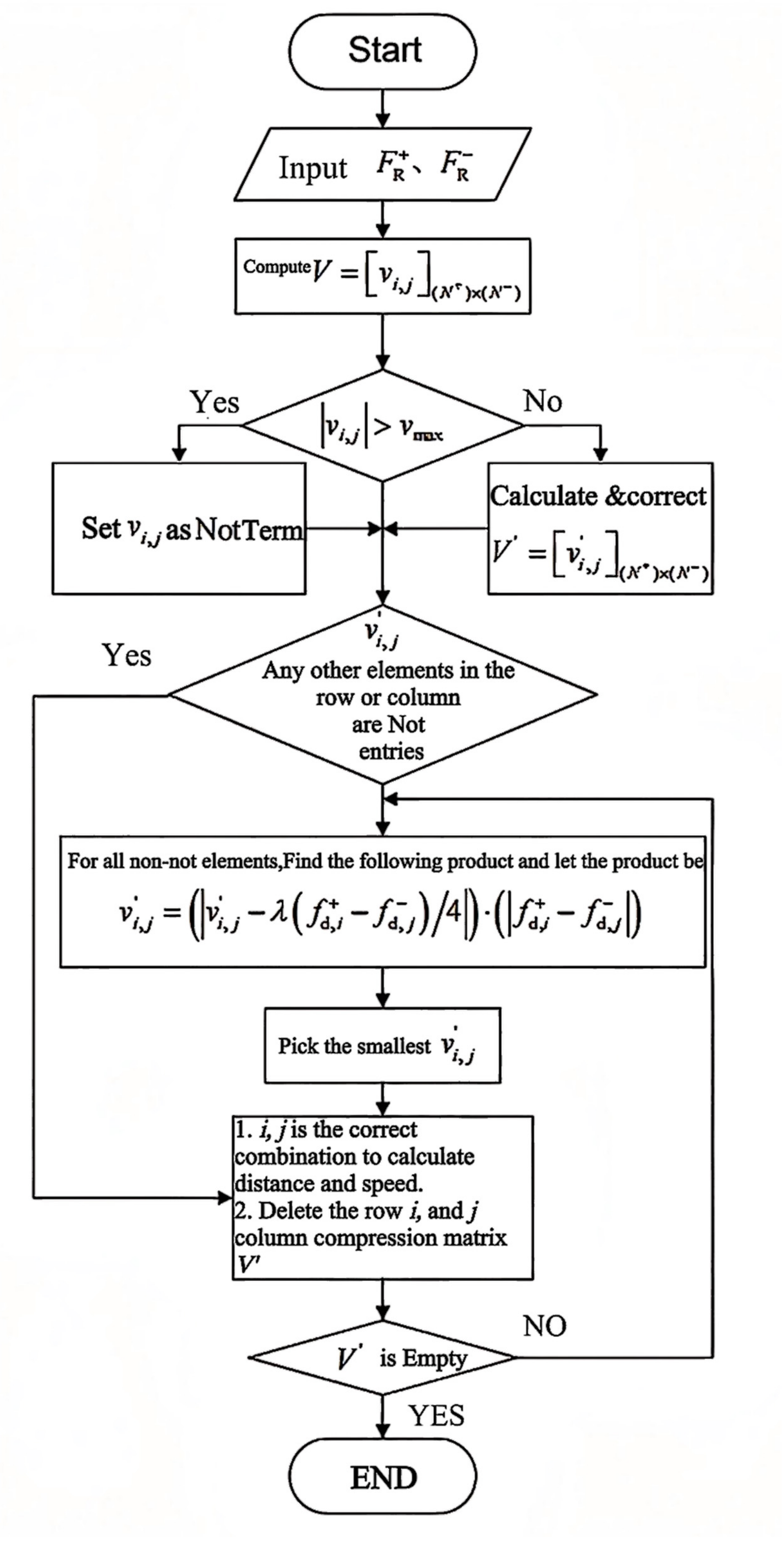

Fig 7. Flowchart of MTD-velocity pairing algorithm

In this study, the beamforming technology is introduced on the basis of the signal processing algorithm structure of "beat - Fourier spectrum analysis -MTD", and the target detection and target range, velocity and angle estimation algorithms are studied. Considering the complex environment of multiple targets, multiple interferers, strong clutter and strong noise, it still overcomes the two major defects of the FMCW radar, which are range-velocity coupling and limited range.

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