An Improved Multi-Target Recognition Method for Vehicle Linear Frequency Modulated Continuous Wave Radar

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Abstract. With the rise of unmanned driving technology and advanced driver assistance systems (ADAS), millimeter-wave radar plays a key role in the field of autonomous driving due to its unique advantages. It can provide forward target information (distance, velocity and angle) for vehicle decision-making and execution systems. Linear frequency modulated continuous wave (LFMCW) automotive radar usually divides the velocity ambiguity resolution and angle estimation into two frames for processing, which will reduce the radar data rate. This paper proposes an improved automotive LFMCW radar multi-target recognition method, which uses the TMD method to transmit sawtooth signals with different time widths and the same bandwidth, and completes range velocity calculation, angle estimation and divides the velocity ambiguity resolution within one frame. This algorithm can simplify the steps of resolving velocity ambiguity and improve the angle measurement accuracy. And it has certain reference significance for the research and application of the LFMCW automotive radar.

1. Introduction

With the rapid development and popularization of autonomous driving technology, as an important sensor of Advanced Driver Assistance System (ADAS), millimetre wave radar is used in automobiles due to its unique advantages such as low cost, small size, long detection range, and high recognition accuracy[1]. How to improve the accurate recognition rate of multi-observed targets by millimetre wave radar has become one of the current research hot spots. In order to improve the angular resolution of millimetre wave radar, multiple-input multiple-output (MIMO) radar is proposed as a new system radar[2].

Compared with single-input single-output radar, MIMO radar transmits and receives signals through multiple antennas, and its recognizability and resolution are significantly improved. Compared with single-input and multiple-output (SIMO) radars, MIMO radar transmits non-interfering waveforms through a set of transmitting antennas (Tx), so that the signals received by the receiving antenna (Rx) are not ambiguous. The receiving antennas form a large virtual array, which greatly improves the angle resolution of the radar. MIMO radar can effectively distinguish multiple targets in front. And MIMO radar is small in size and light in weight. It has good application prospects in automated unmanned driving[3].

Time division multiplexing (TDM) has been widely used in the transmission of MIMO radars because of its simple implementation[4]. TDM means that multiple transmitting antennas transmit signals in turn. In the processing of MIMO radar signals, two-dimensional fast Fourier transform (2DFFT) is used to process the echo signal to obtain the target's angle, velocity and other information, and then the MUSIC algorithm is used to process the corresponding target's angle information.
This paper uses a 77GHz MIMO radar with three transmitters and four receivers, and proposes a new method to improve the distance, velocity and angle information of the target in the multi-target environment of the MIMO radar in one frame, and to solve the problem of velocity ambiguity. There is no matching problem between echo signal and transmitted signal, no multi-target matching problem, and no need to transmit complex waveforms. Compared with the MIMO radar aperture angle measurement method, it can improve the angle resolution and has good application value.

2. System model

MIMO radar can significantly improve the angle resolution of identifying targets through the virtual array. The more receiving antennas, the better the angle resolution of the radar and the smaller the viewing angle. Using phase equivalence between array elements, a three-transmit and four-receiver radar can be equivalent to a one-transmit and twelve-receive radar\(^5\), and it can improve the angular resolution and angle unambiguity of the system\(^6,7\). Antenna arrangement of three-transmit and four-receiver radar is shown in Figure 1. And antenna arrangement of one-transmit and twelve-receive radar which has the same effect with the three-transmit and four-receiver radar is shown in Figure 2.

![Figure 1. Antenna arrangement of three-transmit and four-receiver radar.](image1)

![Figure 2. Antenna arrangement of one-transmit and twelve-receive radar.](image2)

2.1. LFMCW radar beat signal model

77GHz automotive radars often use sawtooth chirp signals as the transmit signal. The mathematical expression of the transmit sawtooth signal \(\text{Tx}(t)\) is

\[
S_r(t) = A \cos \left[ 2\pi \left( f_0 t + \frac{\mu^2}{2} \right) + \varphi_0 \right]
\]

where, \(A\) is the transmitted signal amplitude, \(f_0\) is carrier frequency, \(\varphi_0\) is first phase, and \(\mu\) is modulation slope,

\[
\mu = \frac{B}{T_{\text{chip}}}
\]

where, \(B\) is transmit signal bandwidth, \(T_{\text{chip}}\) is slope period of the transmitted signal.

By modelling and deriving the radar echo signal, the radar beat signal may then be written as

\[
S_M(t) = \frac{1}{2} K_r A^2 \cos \left[ 2\pi \left( f_M t + f_d n T_{\text{chip}} - f_0 \tau_0 + \frac{\mu^2}{2} \right) + \varphi_0 \right]
\]

where, difference frequency \(f_M\) is

\[
f_M = f_d - \frac{2 \mu R}{c}
\]

and \(R\) is the distance of the target, \(c\) is velocity of light, the Doppler shift of the target \(f_d\) is

\[
f_d = \frac{2 \nu}{\lambda}
\]

and \(\nu\) is the velocity of the target, and \(\lambda\) is wavelength. \(K_r\) is reflection coefficient, \(\tau_0\) is the time delay of echo at \(t = 0\), and \(n\) is the total number of slopes.
Since LFMCW radar has the problem of range-velocity coupling, if only using one-dimensional fast Fourier change on the beat note signal, the distance and velocity information of the target cannot be obtained. The two-dimensional fast Fourier transform is used to the radar beat note signal. Fast Fourier transform on the time axis \( t \) can get the difference frequency \( M_f \), so as to find the distance of the target object. On the basis of the one-dimensional Fourier transform, the fast Fourier transform in the direction of the total slope number \( n \) can obtain \( f_s \), so as to obtain the velocity of the target object. Because it is processing multiple periods of beat note signals, there is no problem of mismatch between echo signals and transmitted signals, that is, there is no problem of multi-target matching.

### 2.2. MUSIC algorithm model

Multiple Single Classification (MUSIC) algorithm is a high-resolution Direction of Arrival (DOA) estimation algorithm. The MUSIC algorithm uses the orthogonal characteristics of the signal subspace and the noise subspace to construct the spatial spectrum relationship, and detects the DOA of the signal through searching spectral peak[8].

Use the MUSIC algorithm to calculate the target azimuth. Take the 2D-FFT of the beat matrix and take the modulus to obtain 12 amplitude-frequency characteristic matrices. Then detect the position information of the target detected by the two-dimensional constant false alarm. The order of the antennas is sequentially stored in each row of the receive vector matrix. Decompose the received vector and covariance matrix eigenvalues. According to the order of the eigenvalues, the eigenvector corresponding to the maximum eigenvalue equal to the number of targets is regarded as the signal subspace, and the eigenvector corresponding to the remaining eigenvalues is regarded as the noise subspace. And then construct the spatial spectrum function of the search target angle. In order to facilitate the matching between the target angle and the target, the MUSIC algorithm only recognizes the angle of one target each time.

### 3. New method for solving velocity distance ambiguity and angle measurement

#### 3.1. Radar transmission mode and signal processing

In the traditional method, the signal processing method of LFMCW radar generally divides the distance & velocity measurement and the angle measurement into two frames of signals for processing, as illustrated in Figure 3. This method will prolong the signal processing time and reduce the radar processing rate. This paper proposes a new improved processing method on the original basis.

This method uses time division multiplexing to process the data, and transmits sawtooth frequency modulation signals \( \text{chirp}_1 \), \( \text{chirp}_2 \) and \( \text{chirp}_3 \) with a single period of \( T_{\text{chirp}_1} \), \( T_{\text{chirp}_2} \), and \( T_{\text{chirp}_3} \) on the \( \text{Tx}_1 \), \( \text{Tx}_2 \) and \( \text{Tx}_3 \) transmitting antennas, respectively. The total time of the three antennas transmitting signals must be equal, that is, the relationship between the number of periods \( n_1 \), \( n_2 \) and \( n_3 \) of the modulation signal transmitted by the three antennas may be written as

\[
T_{\text{chirp}_1} n_1 = T_{\text{chirp}_2} n_2 = T_{\text{chirp}_3} n_3
\]  

(6)

The beating signals of the receiving antennas \( \text{Rx}_1 \sim \text{Rx}_4 \), \( \text{Rx}_5 \sim \text{Rx}_8 \) and \( \text{Rx}_9 \sim \text{Rx}_{12} \) are

\[
S_{\text{rf}}(t) = \frac{1}{2} K_c A^2 \cos[2\pi(f_{M_1} t + f_d n_1 T_{\text{chirp}_1} - f_o T + \frac{\mu T^2}{2} + \varphi_0 + (N_1 - 1)\varphi_A)]
\]  

(7)

\[
S_{\text{rf}}(t) = \frac{1}{2} K_c A^2 \cos[2\pi(f_{M_2} t + f_d n_2 T_{\text{chirp}_2} - f_o T + \frac{\mu T^2}{2} + \varphi_0 + (N_2 - 1)\varphi_A)]
\]  

(8)

\[
S_{\text{rf}}(t) = \frac{1}{2} K_c A^2 \cos[2\pi(f_{M_3} t + f_d n_3 T_{\text{chirp}_3} - f_o T + \frac{\mu T^2}{2} + \varphi_0 + (N_3 - 1)\varphi_A)]
\]  

(9)

where, \( f_{M_1} \) is the beat frequency of \( \text{chirp}_1 \), \( \mu_1 \) is the modulation slope of \( \text{chirp}_1 \), \( N_1 \) is the number of the receiving antenna 1~4. \( f_{M_2} \) is the beat frequency of \( \text{chirp}_2 \), \( \mu_2 \) is the modulation slope of \( \text{chirp}_2 \), \( N_2 \) is the number of the receiving antenna 5~8. \( f_{M_3} \) is the beat frequency of \( \text{chirp}_3 \), \( \mu_3 \) is the modulation
slope of chirp3, \( N_j \) is the number of the receiving antenna 9–12. The phase difference caused by the wave path difference is

\[
\varphi_d = \frac{2\pi d \sin \theta}{\lambda}
\]

where, \( d \) is the distance between the receiving antennas, \( \theta \) is the angle of the target.

Perform two-dimensional fast Fourier on the beat signals received by Rx1, Rx5 and Rx9 to obtain the distance and velocity of the target.

Since the maximum detectable velocity \( V_{\text{max}} \) of the radar is limited by the time of a single cycle of the transmitted signal, when the actual velocity of the detected target is higher than the maximum detectable velocity \( V_{\text{max}} \) of the radar, the velocity obtained by Doppler FFT will be ambiguous. Because the single transmission time of the modulated signals transmitted by the three transmitting antennas is inconsistent, which brings three different maximum unambiguity velocity, the velocity expansion algorithm based on Chinese remainder theorem \(^9\) can be used to solve the radar velocity ambiguity problem. This simple velocity extension algorithm can increase the maximum detection velocity of radar in TDM MIMO mode by three times.

3.2. Phase compensation

Because the frequencies of the beat signals of Rx1–Rx4, Rx5–Rx8, and Rx9–Rx12 are different during the three transmission and reception processes, the target echo signal received by different antennas will cause a phase difference. This phase difference will be coupled with the phase difference produced by the frequency modulation slope during the calculation of the target's distance and velocity values, which will increase the angle estimation error. Therefore, it is necessary to compensate the phase difference of the beat signals received by Rx5–Rx8 and Rx9–Rx12 before calculating the angle.

Phase compensation value of Rx5–Rx8 is

\[
X_{5-8}(t) = \cos \left\{ 2\pi \frac{(f_{M1} - f_{M2}) n_s}{f_s} + \frac{\tau_0^2}{2} (\mu_1 - \mu_2) \right\}
\]

where, \( n_s \) is sampling points, \( f_s \) is sampling rate. Phase compensation value of Rx9–Rx12 is

\[
X_{9-12}(t) = \cos \left\{ 2\pi \frac{(f_{M1} - f_{M3}) n_s}{f_s} + \frac{\tau_0^2}{2} (\mu_1 - \mu_2) \right\}
\]

After the phase compensation of the beat signal, the MUSIC algorithm is used to calculate the target angle. The flow chart of MIMO radar signal measuring range speed and angle measuring method with one frame of signal is shown in Figure 4.

![Figure 3. Traditional MIMO radar signal processing flow.](image1)

![Figure 4. A new method for solving velocity ambiguity angle measurement.](image2)
4. Simulation results and analysis

Use MATLAB to simulate and verify the designed model and algorithm. The MIMO radar parameters are designed as follows: carrier frequency $f_0 = 77$GHz, signal modulation bandwidth $f_{sw} = 100$MHz.

Table 1. gives the modulation signal parameters, Table 2. gives the single simulation target parameter, and Table 3. gives the multi simulation target parameter.

| Table 1. Modulation signal parameters. |
|----------------------------------------|
| Tx1 signal    | Tx2 signal    | Tx3 signal    |
| slope period /μs | 20            | 15            | 25            |
| Number of modulation periods | 150           | 200           | 120           |

| Table 2. Single simulation target parameter. |
|---------------------------------------------|
| range/m | velocity (m/s) | angle/° |
| Single target | 15             | 40            | 13            |

| Table 3. Multi simulation target parameter. |
|---------------------------------------------|
| range/m | velocity (m/s) | angle/° |
| Target 1 | 75             | 25            | 19            |
| Target 2 | 45             | -5            | 27            |

Figure 5 ~ Figure 8 give the simulation results of the distance, velocity after 2DFFT and target angle recognized by a single target. In Tx1 and Tx2 antennas, the distance absolute value error of a single target is less than 1m. The velocity measurement of a single target is within the maximum velocity that can be measured by the Tx1 and Tx2 antennas, so the velocity measurement is not ambiguous. And the absolute value error of the measurement is less than 0.5m/s. In Tx3 antenna, the single target velocity is outside the maximum velocity that can be measured. Use the above method to resolve the velocity ambiguity. The maximum velocity that the Tx3 antenna can measure is 38.961m/s, and the measured value after velocity compensation is 40.18 m/s. The absolute value error of measurement is less than 0.5m/s. The absolute value error of the single target angle is less than 0.1°, which meets the expected angle measurement performance index.

Figure 5. RX1 recognizes the speed and distance results of a single target.  
Figure 6. RX5 recognizes the speed and distance results of a single target.
Figure 7. RX9 recognizes the speed and distance results of a single target.

Figure 8. Single target MUSIC algorithm result.

Figure 9 ~ Figure 13 give the simulation results of the distance, velocity after 2DFFT processing and target angle recognized by multi-target. The distance absolute value errors of multi-target are less than 1m. The velocity measurement of multi-target is within the maximum velocity that can be measured by the Tx1, Tx2 and Tx3 antennas, so the velocity measurement is not ambiguous. And the absolute value errors of the measurement are less than 0.5m/s. The absolute value errors of the multi-target angles are less than 0.1°, which meet the expected angle measurement performance index.

Figure 9. RX1 recognizes the speed and distance results of multi-target.

Figure 10. RX5 recognizes the speed and distance results of multi-target.

Figure 11. RX9 recognizes the speed and distance results of multi-target.

Figure 12. Angle of Target 1.
Figure 13. Angle of Target 2.

The simulation results of single target and multi-target verify the feasibility of the method proposed in this paper. It can achieve target recognition with absolute distance error less than 1m, absolute velocity error less than 0.5m/s, and absolute target angle error less than 0.1°. In the case of dense targets, simulation experiments have also been carried out to verify the feasibility of the method. However, due to the limitations of the DOA-MUSIC algorithm, the computational complexity is relatively high, and the noise subspace is required to construct the spatial spectrum function. This method can only identify the number of element antennas minus one targets. For the radar of three transmitters and four receivers, the MUSIC algorithm can only detect up to 11 targets at the same time. Under the premise of consistent angle measurement performance, compared with the traditional method which dividing the signal into two frames for processing, the method proposed in this paper can obtain the true speed, distance and angle of the target within one frame of signal processing time, which can reduce radar signal processing time by half. And the signal processing time can effectively improve the data rate of the radar.

5. Conclusion

MIMO radar has become the research direction of LFMCW vehicle radar. It mainly uses modulated sawtooth signal to obtain the distance and velocity information of the targets. Generally, two frames of signals are used to calculate the distance, velocity and angle of the targets. This paper proposes a new method to improve the distance, velocity and angle information of the target in the multi-target environment of the radar with three transmitters and four receivers in one frame, and to solve the problem of velocity ambiguity. Modulated signals of different slopes with the same total time are transmitted by three transmitting antennas in one frame, then the true distance, velocity and angle information of the target can be obtained in one frame. In the measurement angle, the angle measurement method of processing the 2D-FFT information to construct the spatial spectrum is used, which effectively improves the angle resolution and the angle measurement accuracy of the MIMO radar detection. The next step will be to optimize the waveform and algorithm, enhance the detection and resolution capabilities of real targets, and further improve the detection capabilities of the vehicle-mounted MIMO radar.

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