Research on Multi-target Signal Separation and Processing Method

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Abstract. Nowadays, intelligent cities and transportation are being implemented in major cities around the world. In unmanned vehicles, autonomous identification and separation of moving targets is the essential and important part of intelligent transportation. This paper proposes a multi-object separation algorithm in order to solve the security problems that can promote smart transportation. This paper deals with multi-target signals based on MATLAB. In terms of distance, between the cars (targets) that can be separated, multiple targets are separated by matched filter and FFT algorithm, then the performance of the research is expressed by distance resolution. The separable target distance is up to 200 m, and the resolution is up to 0.6 m; in the terms of speed, multiple targets are separated by the Doppler transform, then the performance of the research is reflected in the form of speed resolution. The speed at which the separated target can be identified is up to 200km/h, and the resolution is up to 1.8km/h, otherwise, both stationary and moving targets can be identified. Finally, all the results are obtained by MTALAB simulation.

Keywords: Multi-object separation; Matched filter; FFT algorithm.

1. Introduction
With the emergence of the concept of intelligent cities and the rapid development of science and technology, the transportation infrastructure is imperfect, and various traffic problems are also coming. In order to better solve this problem, the intelligent transportation system (ITS) was developed and use. Target detection and separation in ITS is a widely used core technology. According to the traditional direct analysis method, it can no longer be effectively and quickly processed, but the performance of the computer is getting better and better, which provides a new way for the radar simulation processing. Using a computer to simulate radar, on the one hand, the simulation can be completed at the lowest possible cost. On the other hand, this is also a very flexible method, which can be used to simulate the radar multiple times without being limited by time, and has high operability. It also facilitates the analysis of radar signals. It can generally be considered that the radar's transmitted wave forms an echo signal after delay and Doppler shift. All information content in the radar signal is composed of the modulation of the radar transmit wave, which is the basic theory and principle of the analog radar signal. The key to analog radar is to simulate the radar's echo signals and the propagation characteristics of the clutter.

Generally, methods for achieving multi-target signal separation include neural network algorithm, Wiener filtering, blind signal estimation, etc. These methods have been widely used in many fields, at the same time have certain disadvantages, neural network algorithms, the disadvantage is that the data cannot be processed quickly; The Wiener filtering method needs to first know the statistical
characteristics of the input process; Since the external environment is changing at all times, the blind signal estimation method cannot solve the problem of anti-noise interference well. In this paper, the received signal is subjected to Fourier transform and other processing to obtain the spectrum of the signal, which is filtered from the two levels of distance and velocity. When the distances of the two targets are the same, they can be filtered from the velocity level, achieving separation. The main idea of multi-target signal separation in this paper is to first perform Fourier matching filtering on the received radar signal to obtain the distance information of the target. Then, using the Doppler transform, the velocity information of the target can be obtained, through the three dimensions of distance-speed-amplitude, a distance-speed-amplitude three-dimensional map can be drawn on the coordinate axis. The distance-amplitude two-dimensional image can be drawn by the distance-amplitude two dimensions. The velocity-amplitude two-dimensional image can be drawn through the two dimensions of velocity-amplitude, so that different target signals in the radar signal can be visually seen distance, speed, amplitude and other information.

2. The Principle of the Multi-target Signal Separation Algorithm

2.1. FFT Transform

FFT is one of the discrete Fourier algorithms and is a very fast algorithm, also known as the Fast Fourier algorithm. FFT has the properties of parity and the characteristics of imaginary part and real part. By improving the discrete Fourier transform, a fast Fourier transform (FFT) algorithm is obtained. A complex sequence x(m) of M terms is provided, and for any sequence X(m), M-1 complex addition and M complex multiplication operations are required for performing discrete Fourier transform. In general, in the DFT, each multiplication operation is equivalent to multiplication of 4 times the number of real numbers plus addition of 2 times. If the complex number is added, it is equivalent to adding 2 times the number of real numbers. Usually in DFT, on a complex number, m basic operations include m multiplications and additions. The addition and multiplication of 4m times on the real number is equivalent to the basic operation of m times. Setting X(m) be a sequence of M times, and in order to calculate X(m), it is necessary to perform a square operation of M. When the number of points is 2048, 4194304 operations are required, and there are two properties in the transformation of the FFT, one is periodicity and the other is symmetry. If you use the fast Fourier transform method to calculate, the number of operations required is 2099200, which is almost half of the number of direct calculations required 4194304. Let the sequence x(n) be N and define the N-point DFT of x(n) as:

\[ X(k) = DFT[x(n)]_N = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi kn}{N}}, k = 0,1,...,N-1 \]  

(1)

In the equation, N is the length of the interval required for DFT transformation. For the convenience of writing, define \( W_N = e^{-\frac{2\pi}{N}} \), therefore, the discrete Fourier of the N point is usually expressed as:

\[ X(k) = DFT[x(n)]_N = \sum_{n=0}^{N-1} x(n)W_N^{kn}, k = 0,1,...,N-1 \]  

(2)

The N-point inverse Discrete Fourier transform (IDFT) that defines X(k) as:

\[ x(n) = IDFT[X(k)]_N = \frac{1}{N} \sum_{n=0}^{N-1} x(k)W_N^{-kn}, n = 0,1,...,N-1 \]  

(3)

2.2. 2-base Algorithm for Frequency Domain Extraction

By definition:
Divide \(f(n)\) into \(f(n)\) and \(\left\lfloor \frac{n}{2} \right\rfloor\) parts and substitute it into the above formula:

\[
F[k] = \sum_{n=0}^{N/2-1} \{f[n]+(-1)^k f[n+N/2]\} W_{N/2}^{kn} \quad 0 \leq k \leq N-1
\]

When \(k=2r\) is even number, because of \((-1)^r = 1\), \(W_N^{kn} = W_N^{2rn} = e^{-i2\pi 2rn/N} = W_{N/2}^{rn}\), then

\[
F[2r] = \sum_{n=0}^{N/2-1} (f[n]+f[n+N/2]) W_{N/2}^{rn}
\]

\[
= \sum_{n=0}^{N/2-1} g(n) W_{N/2}^{rn}
\]

\[
= G(r) \quad 0 \leq r \leq N/2 - 1
\]

When \(k=2r+1\) is odd number, because of \(W_N^{kn} = W_N^{(2r+1)n} = e^{-i2\pi (2r+1)n/N} = W_{N/2}^{rn} W_{N/2}^{rn}\), then

\[
F[2r+1] = \sum_{n=0}^{N/2-1} \{(f[n]-f[n+N/2]) W_{N/2}^{rn} W_{N/2}^{rn}
\]

\[
= \sum_{n=0}^{N/2-1} p(n) W_{N/2}^{rn}
\]

The DFT operation of \(N\) points for \(f[n]\) can be divided into two parts of \(g[n]\) and \(p[n]\). Where \(g[n]\) is the \(N/2\) point, the DFT operation is performed on the even part of \(f[n]\), and \(p[n]\) is also the \(N/2\) point, which performs the DFT operation on the odd part of \(f[n]\). The output of DFT(G(r)) of \(g[n]\) is an even part of \(F[k]\), and the output of DFT(P(r)) of \(p[n]\) is an odd part of \(F[k]\). This algorithm is performed on the variable \(k\) in the frequency domain, so it is also called the FFT algorithm of frequency domain extraction. If you have two \(N/2\) DFTs already in place, continue with this method. It can be known that it takes \(N/4\) multiplications and \(N/2\) additions to divide the two parts into \(N/4\) points DFTs, so a total of \(N\) additions and \(N/2\) multiplications are required. Step by step in this way, it can be seen that for each such operation, \(N\) plus and \(N/2\) multiplication operations are required. After \(N\) times, I get the following formula:

\[
A = a W_2^{00} + b W_2^{01} = a + b
\]

\[
B = a W_2^{10} + b W_2^{11} = (a - b) \cdot W_2^{01}
\]

The above equation requires 2 additions and 1 multiplication. It can be concluded that \(N/2\) two-point DFTs require a total of \(N\) additions and \(N/2\) multiplication operations. Therefore, in order to complete the DFT of the \(N\) point, a total of \(M \times N/2 = (\frac{N}{2}) \log_2 N\) additions and \(M \times N/2 = (\frac{N}{2}) \log_2 N\) multiplications are required. However, if you calculate directly according to the definition, you need the operation of \(N^2\) additions and multiplications, and the calculation amount is far more than the FFT operation.

In general, the \(M\) times of this algorithm are calculated separately according to the odd part and the even part. For the \(M\) time, the sequences after the DFT of these two points are not listed in order, the binary code can be used to express this order. The first time is to distinguish the odd part from the even part according to the first digit of the binary code. The first digit is 1 for the odd part, and the first digit is 0 for the even part. The second time is divided according to the second digit of the binary code, to see if it is 0 or 1, and it has been carried out in this way. Each division is to put the even part on the right, the odd part on the left, and then arrange from left to right according to the binary. The sequence after
alignment is the opposite of right-to-left alignment, call this the reverse order. After completing the F[k] operation, the inversion order needs to be processed to make it into order.

2.3. 2-Base Algorithm for Time Domain Extraction

Setting the sequence have $N = 2^L$ points, where L is an integer. If the number of points is not enough, you can add 0 at the end.

Using the 2-base according to the time domain decimation (DIT) decomposition method, the decimation decomposition according to the parity relationship in the time domain can be obtained: $A + BW_N^r$

Assuming $x(2m) = a(m)$, $x(2m+1) = b(m)$. Because of $W_{2mk}^2 = W_{mk/2}^2$, so

$$X(k) = \sum_{m=0}^{N/2-1} a(m)W_{mk/2}^N + W_{k}W_{m/2}^N \sum_{m=0}^{N/2-1} b(m)W_{mk/2}^N$$

Reorder $A = \sum_{m=0}^{N/2-1} a(m)W_{mk/2}^N$, $B = \sum_{m=0}^{N/2-1} b(m)W_{mk/2}^N$, $W_{mk/2}^r = W_{mk/2}^r$, then

$$X(k) = A + BW_N^r$$

$$X(k+N/2) = A - BW_N^r$$

(10)

We can use the butterfly signal flow diagram below to express the operations of the above two equations.

2.4. Match the Principle of Filtering

In modern digital communication systems, there are two main factors that affect communication performance: the transmission characteristics of the channel and the noise during transmission. In order to achieve the best transmission performance under the same transmission conditions, it is necessary to effectively detect the expected signal, that is, the best reception, in the noise interference. There are two criteria for applying: the error probability minimum criterion and the output signal to noise ratio maximum criterion. In general, the signal-to-noise ratio is the ratio of the instantaneous power of the signal to the average power of the noise at a certain moment. The larger the signal-to-noise ratio, the less likely it is to make a false decision. Among all the filters, one has the largest output signal-to-noise ratio and is the best linear filter.

In the case where the input is a known signal and white noise is added, the matched filter is a filter that maximizes the signal-to-noise ratio of the output. For example, the signal input to a linear filter is $x(t)$, then $x(t) = s(t) + n(t)$.

The input signal energy is $E(S) = \int_{-\infty}^{\infty} S^2(t)dt < \infty$. The input signal spectrum function is $S(\omega) = \int_{-\infty}^{\infty} S(t)e^{-j\omega t} dt$. The output signal spectrum function is $S_0(\omega) = H(\omega)S(\omega)$. The average power of the output noise is:
\[ E[n_0^2(t)] = \frac{1}{2\pi} \int_{-\infty}^{\infty} P_n(\omega) d\omega = \frac{1}{2\pi} \int_{-\infty}^{\infty} H^2(\omega) P_n(\omega) d\omega \] (11)

Using the Schwarz inequality to get:

\[ SNR_0 \leq \frac{1}{2\pi} \int_{-\infty}^{\infty} \left| \frac{S(\omega)}{P_n(\omega)} \right|^2 d\omega \] (12)

When the input power spectral density of the filter is \( P_n(\omega) = N_0 / 2 \) white noise, the system function of MF is \( H(\omega) = kS^* e^{-j\omega \phi} \), \( k = \frac{2a}{N} \).

Where \( E_s \) is the energy of the input signal \( s(t) \), and the power spectrum of the white noise \( n(t) \) is \( N_0 / 2 \).

When the input signal is a real function, the expression of the impulse response of the matched filter of \( s(t) \) is \( h(t) = k s(t - \phi) \). \( k \) is the relative amplification of the filter, usually taking \( k = 1 \).

Model of the matched filter:

**Figure 2.** Model of the matched filter.

### 3. Speed Measurement Based on Doppler Effects

The Doppler effect refers to the phenomenon that the wavelength of radiation of the target object changes due to the relative motion between the wave source and the target object. When the wave source moves behind the target object, the wave will be compressed, the wave will become shorter, and the wave frequency will be higher than the original one; when the wave source moves in front of the target object, the wave will be pulled up, it will become longer and the frequency of the wave will become lower.

The sound wave velocity is divided into two parts: the transmitted wave and the received wave. In the part of the transmitted signal, the Doppler sonic speedometer emits a wave, and the moving target receives the transmitted wave. In this process, the Doppler sonic speedometer acts as a wave source and is stationary, while the moving target acts as a wave receiver and moves at a velocity \( v \). Set the frequency of the Doppler sonic speedometer to be \( f_0 \), the acoustic wave received by the moving target is \( f_1 \), and the acoustic wave propagation velocity is \( v_0 \), then \( f_1 = \frac{v_0 - v}{v_0} f_0 \).

In another part, the moving object acts as a wave source at a velocity \( v \), and the Doppler sonic speedometer is stationary as a receiver. Set the frequency received by the Doppler sonic speedometer to \( f_2 \), and the frequency of the sound wave reflected by the moving object is \( f_1 \), so you can get \( f_2 = \frac{v_0 + v}{v_0} f_0 \). Conclusion we will get, namely

\[ v = \frac{f_2 - f_0}{f_0} v_0 \] (13)
It can be seen from the above equation that the moving velocity \( \psi \) of the moving object is related to the reflected wave frequency \( f_2 \) of the Doppler shift received by the Doppler acoustic velocity meter, the transmitted wave frequency \( f_0 \), and the propagation velocity \( v_0 \) of the acoustic wave.

4. Design of Multi-objective Signal Separation Algorithm

4.1. Design of the Transmit Signal Module and Design of the Echo Signal Module

The mathematical expression of the modulated signal is:

\[
s(t) = \text{rect}\left(\frac{t}{T}\right)e^{j2\pi(f_0 + \frac{B}{T}t)^2}
\]  

(14)

Where \( f_0 \) is the carrier frequency and \( \text{rect}\left(\frac{t}{T}\right) \) is the rectangular signal:

\[
\text{rect}\left(\frac{t}{T}\right) = \begin{cases} 1 & \left|\frac{t}{T}\right| \leq 1 \\ 0, \text{otherwise} \end{cases}
\]

(15)

\( \frac{B}{T} \) is the slope of the frequency modulation, so the instantaneous frequency of the signal can be obtained as \( f_0 + \frac{B}{T}t \), while \( -\frac{T}{2} \leq t \leq \frac{T}{2} \).

The carrier frequency of the transmitted signal is set to 24 GHz, the pulse width of the signal is 0.25 ms, and the linear frequency modulation bandwidth is 250 MHz. Draw the image of the echo signal through MATLAB and get the time domain and spectrum of the transmitted signal.

4.2. The Design of Matching Filter Module

![Matched filter flow chart](image)

The echo signal \( S_{rt} \) is first subjected to FFT conversion, and then conjugate-multiplied with the IFFT of the reference signal \( H(t) \), and then the IFFT operation is performed to obtain the filtered signal \( S_{ot} \). The image of \( S_{ot} \) can be drawn by MATLAB.

4.3. The Design of Ranging Module and Speed Measuring Module

The ranging is performed by processing the matched signal \( S_{ot} \) obtained by filtering. The matched filtered \( S_{ot} \) will have an impulse response in amplitude at the distance corresponding to the target. For the signal \( s(t) \), the impulse response of its matched filter in the time domain can be expressed as \( h(t) = s*(t_0 - t) \).

The speed measurement is to first calculate \( |f_2 - f_1| \) for each target, then calculate the speed of each target according to the formula of Doppler effect: \( v = \frac{c}{2f_0} \left|\frac{f_2 - f_1}{2}\right| \), use \( v \) as the abscissa, and match the filtered \( S_{ot} \) as the ordinate, draw the picture through MATLAB, speed-amplitude image is available.

5. Test Results and Analysis

A signal with three targets is set. The carrier frequency of the transmitted signal is 24 GHz, the pulse width of the signal is 0.25 ms, the linear frequency modulation bandwidth is 250 MHz, and the number
of echo signals is set to 50 times. The distance resolution is 0.6m and the speed resolution is 1.8km/h.

1) Transmitted signal module:

Figure 4. Time domain diagram of the transmitted signal.

Figure 5. Spectrogram of the transmitted signal.

Figure 4. is a plot of the transmitted signal \( S_t = e^{j \pi t^2} \), and Figure 5 is a spectrogram obtained by performing an FFT transform of the transmitted signal at 524288 points.

Figure 6. Spectrogram of echo without Gaussian white noise.

Figure 7. Spectrogram of echo with Gaussian white noise.

Figure 8. Matched radar echo spectrum before filtering.

Figure 9. Matched filtered radar echo spectrum.

2) Echo signal module and Matched filter module:

The signal is subjected to 524288 points FFT transformation, and the amplitude of the FFT signal is taken as the y-label and the frequency sequence is taken as the x-label. After simulation, it is obtained as shown in Figure 6.

The FFT is applied to the noise-added signal in the same manner as the un-noise, and finally the spectrum of Figure 7. is obtained. It can be seen from Figure 6 and Figure 7 that the spectrum of the signal is smoother before noise is added.

By plotting the spectrograms Figure 8. and Figure 9. before and after matching filtering, it can be seen that the filtered signal spectrum is smoother, and most of the burrs are eliminated, resulting in a better signal spectrum. Matching filtering plays an important role.

Figure 10. Ranging module displays results.

Figure 11. Speed measurement module displays results.

Figure 12. Overall display module results.
3) Ranging and speed measuring module:
As shown in Figure 10. and Figure 11., the distances and speed of the three targets set are all separated
totally, which are 10 m, 50 m, 90 m, 25m/s, 40m/s and 50m/s, respectively.
The speed-distance-amplitude is plotted as a three-dimensional Figure 12., which can better reflect the
position and velocity information of multiple separated targets. It is more suitable for simulating an
unmanned environment.

Table 1. After 4 tests, the change of range resolution and speed resolution.

| Testing frequency | Number of targets | Frequency modulation frequency | Distance resolution | Speed resolution |
|-------------------|-------------------|--------------------------------|---------------------|------------------|
| 1                 | 4                 | 100 MHz                        | 1.5 m               | 0.5m/s           |
| 2                 | 4                 | 150 MHz                        | 1.0 m               | 0.5m/s           |
| 3                 | 4                 | 250 MHz                        | 0.6 m               | 0.5m/s           |
| 4                 | 3                 | 250 MHz                        | 0.6 m               | 0.5m/s           |

It can be seen from the test results that in the case of three or four targets, the system can well separate the
distance and velocity information of each target signal, and in the overall display module, the separated
multiples can be seen, a three-dimensional image of the distance-speed-amplitude of the target.

6. Summary
In this paper, the simulation can be realized in various situations by setting different parameters. From
the results, the wider the bandwidth, the higher the distance resolution.
The design has a carrier frequency of 24GHz, a bandwidth of 250MHz, a pulse width of 0.25ms, and a
set resolution of 50 times. About distance, the separation targets can reach 200m, and the distance
resolution is up to 0.6m. About speed, the separation targets can reach 200km/h, and the speed resolution
is relatively high, respectively 1.8km/h. Combining speed and distance, we can even separate moving
targets with a distance of zero. Using MATLAB rich execution methods, fast debugging speed and high
programming efficiency, it is easy to simulate different situations.
In modern digital signal reception, the matched filtering can achieve the maximum signal-to-noise ratio
of the output when the input is a known signal with white noise, thereby measuring the distance of
multiple targets. The Doppler velocity measurement method is used to measure the speed of multiple
targets. Using the parity and imaginary realism of the Fourier transform, the fast Fourier transform
algorithm is obtained. The algorithm has the advantages of small computation, convenient sampling, fast
calculation speed and convenient programming, which are very suitable for use in computers.
Unfortunately, this design does not analyse the target angle, so we will start from the aspect of the angle
measurement.

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