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Two-dimensional FFT and two-dimensional CA-CFAR based on ZYNQ

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Abstract: Here, two-dimensional FFT and two-dimensional CA-CFAR are combined to process echoes of LFMCW radar based on ZYNQ, which are implemented on hardware, using parallel feature of ZYNQ to improve processing speed. With the high accurate information of two-dimensional FFT and two-dimensional CA-CFAR, the velocity and range information of echo signal is extracted. The coupling problem of velocity and range is solved and the situation of alarm leakage in multi-target is avoided. First, the basic form of the LFMCW signal is introduced. Then, the implementation flow of 2D-FFT and 2D CA-CFAR is described in detail. At last, the conclusion is given by analysing the results of the tested data processed by ZYNQ and is compared with 1D-FFT combined with 1D-CFAR.

1 Introduction

LFMCW radar has a wide application prospect in the field of automotive radar because of the characteristic of its large time-bandwidth product, small peak power, and low interception [1]. There are two kinds of common LFMCW: one is sawtooth wave and the other is triangular wave [2, 3]. In order to solve the problem of distance velocity coupling, the triangular wave system is generally adopted. Yi [4] proposed an algorithm for measuring range and velocity using echo signal of triangular wave mixed with local waveforms. After signal mixed, two different beat-frequencies will be measured by one-dimensional FFT and one-dimensional cell-average constant false-alarm rate (CA-FAR). Then, the range and velocity can be calculated, respectively, thus solving the problem of range-velocity coupled. However, the method is not ideal for detecting multi-moving targets in fixed clutter, and it is easy to generate false targets among different clutters. At the same time, the performance will decrease when the velocity is not uniform or changes quickly in a complex environment with a large number of targets. In addition, one-dimensional FFT cannot accurately estimate the Doppler frequency, so that the accuracy of velocity decreases; on the other hand, because the reference window of one-dimensional CFAR detector is on the same dimension, that is, on the range dimension or the Doppler dimension. So, the background information obtained is simple, thus the estimation of noise being not accurate, leading to poor threshold [5]. Therefore, in order to obtain more background information and to eliminate the problem of range-velocity coupled, the two-dimensional FFT (2D-FFT) is used, that is, the background information on Range and Doppler dimension is selected simultaneously. When 2D-FFT is used, CA-CFAR will be extended to two-dimension (2D CA-CFAR) with rapid sawtooth wave. This method also simplifies the transmitting mode and reduces the complexity of the modulating signal. With regard to 2D CA-CFAR [6–9], Matthias Kronauge presented a theoretical implementation scheme for fast 2D CFAR, which combines CA-CFAR with OS-CFAR (Order-statistic CFAR) [10]. However, if the scheme is implemented on ZYNQ, it will increase the complexity of the program. As OS-CFAR needs to be sorted first and then abstracted, which takes a lot of time.

In order to detect multiple targets and estimate the speed and distance information of each target in real-time in automotive radar application, the 2D-FFT and 2D CA-CFAR with rectangular sliding window are implemented based on the ZYNQ in this paper. The fast sawtooth wave signal is used to simplify the processing. The results of experiment prove that the proposed scheme is feasible.

2 Analysis of LFMCW signal in vehicle radar

The signal transmitted by radar is a sawtooth wave, and its expression in one modulation period is:

$$s(t) = A\cos\left(2\pi\left[(f_0 + B/2)t + \frac{1}{2}\mathrm{Kt}^2\right] + \varphi_0\right), \quad t \in [0, T] \tag{1}$$

where f_0 is the central frequency, $K = B/T$ is the slope of modulated frequency, B is the modulation bandwidth, φ_0 is the initial phase, T is the modulation period, A is the signal amplitude.

The instantaneous phase of the transmitted signal can be expressed as:

$$P_T(t) = 2\pi\left[(f_0 + B/2)t + \frac{1}{2}\mathrm{Bt}^2\right] + \varphi_0, \quad t \in [0, T] \tag{2}$$

when t is 0, in the field of radar beam, one target has a radial velocity v with distance of R_0. Then, the radar echo signal will have a delay, at this time the instantaneous phase of the echo can be expressed as:

$$P_R(t) = 2\pi\left[(f_0 + B/2)(t - \tau) + \frac{1}{2T}B(t - \tau)^2\right] + \varphi_0 \tag{3}$$

After the received target's echo signal and the transmitted signal are mixed, the beat-frequency signal is obtained and the phase of the beat-frequency signal is as follows:

$$\begin{aligned} P_M(t) &= P_T(t) - P_R(t) \\ &= 2\pi\left\{(f_0 + B/2)\tau + \frac{1}{2T}B\left[t^2 - (t - \tau)^2\right]\right\} \\ &= 2\pi\left\{\frac{2}{c}(f_0 + B/2)v - \frac{4\mathrm{BR}_0 v}{Tc^2} + \frac{2\mathrm{BR}_0}{Tc}\right. \\ &\quad \left. + \left(\frac{2Bv}{Tc} - \frac{2Bv^2}{Tc^2}\right)t^2 + \frac{2R_0}{c}(f_0 + B/2) - \frac{2\mathrm{BR}_0^2}{Tc^2}\right\} \end{aligned} \tag{4}$$

The beat-frequency signal of moving target is still linear FM Signal. The main parameters of the signal are as follows:

Echo signal's Bandwidth is:

$$B_r = \frac{4\mathrm{Bv}}{c} - \frac{4\mathrm{Bv}^2}{c^2} \tag{5}$$

Echo signal's central frequency is:

$$\begin{aligned} f_r &= \frac{2\mathrm{BR}_0}{\mathrm{Tc}} + \frac{2\mathrm{vf}_0}{c} - \frac{\mathrm{Bv}}{c} - \frac{4\mathrm{BR}_0 v}{\mathrm{Tc}^2} + \frac{2\mathrm{Bv}^2}{c^2} \\ &\simeq \frac{2\mathrm{BR}_0}{\mathrm{Tc}} + \frac{2\mathrm{vf}_0}{c} \end{aligned} \tag{6}$$

Echo signal's initial phase is:

$$\varphi_r = 2\pi\left[\frac{2R_0}{c}(f_0 + B/2) - \frac{2\mathrm{BR}_0^2}{\mathrm{Tc}^2}\right] \tag{7}$$

So the beat-frequency signal can be expressed as:

$$r(t) = A_r \cos\left\{\left[2\pi(f_r + B_r/2)t + \frac{1}{2T}B_r t^2\right] + \varphi_r\right\} \tag{8}$$

Its complex signal is expressed as:

$$r(t) = \exp(j\varphi_r)A_r \exp\left\{j2\pi\left[(f_r + B_r/2)t + \frac{1}{2T}B_r t^2\right]\right\} \tag{9}$$

with the above formula, the central frequency f_r of the echo is related to R_0 and v. However, it is difficult to estimate the radial velocity of the target due to the small change of f_r during the adjacent sweep period. However, the signal envelope $A_r\exp(j\varphi_r)$ of the target will show a large change. In the sweep period, its complex envelope is showed:

$$\begin{aligned} A_r\exp(j\varphi_r) &= A_r \exp\, j2\pi\left[\frac{2R_0}{c}(f_0 + B/2) - \frac{2\mathrm{BR}_0^2}{Tc^2}\right] \\ l &= 0, 1, \ldots, M \end{aligned} \tag{10}$$

Its central frequency exactly reflects the velocity information of the target, and its corresponding relation is:

$$f_v = \frac{2(f_0 + B/2)v}{c} - \frac{4\mathrm{BR}_0 v}{Tc^2} \simeq \frac{2(f_0 + B/2)v}{c} \tag{11}$$

That is, if we get f_v, we get the target velocity.

3 Two-dimensional FFT processing of echo

In the two-dimensional processing of LFMCW radar signal, the echo of many periods should be accumulated first. Then the echo should be arranged into a two-dimensional matrix according to the period as Fig. 1. By FFT of the two-dimensional matrix, the frequency information corresponding to the range and velocity of the target can be obtained.

Assuming the radar echo sequence $x[n]$ is as shown in Fig. 2. The length of $x[n]$ is N, so DFT is:

$$X[k] = \sum_{n=0}^{N-1} x[n]W_N^{\mathrm{nk}}, \quad k = 0, 1, \ldots, N-1 \tag{12}$$

where N are equal to $M \times L$.M are sampling points per cycle, L is number of echo cycles accumulated. Then $x[n]$ is rearranged to get one matrix with L row, M column. Assuming that $n = \mathrm{Mn}_1 + n_0$

$$\begin{gathered} (n_1 = 0, 1, \ldots, L-1, n_0 = 0, 1, \ldots, M-1) \\ k = \mathrm{Lk}_1 + k_0 \\ (k_1 = 0, 1, \ldots, M-1, k_0 = 0, 1, \ldots, L-1) \end{gathered} \tag{13}$$

when n, k are substituted into $X[k]$, it is sorted to get:

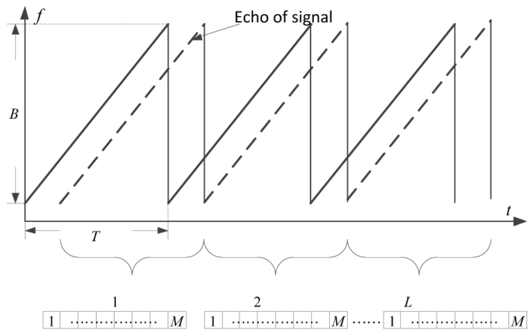

Fig. 1 *Echo signal of LFMCW*

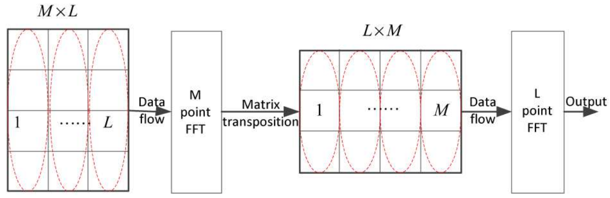

Fig. 2 *2D-FFT processing flow*

$$\begin{aligned} X[k] &= X[\mathrm{Lk}_1 + k_0] = X[k_1, k_0] \lim_{x \to \infty} \\ &= \sum_{n=0}^{N-1} x[n]W_N^{\mathrm{nk}} \\ &= \sum_{n_0=0}^{M-1}\left\{\left[\sum_{n_1=0}^{L-1} x[n_1, n_0]W_L^{n_1 k_0}\right]W_N^{n_0 k_0}\right\}W_M^{n_0 k_1} \end{aligned} \tag{14}$$

The FFT with L points in square brackets is a total of M in the above. The sum of the outer layer is the FFT with M point, which is a total of L. This converts one-dimensional FFT with a length of N into a two-dimensional FFT of a matrix.

When ZYNQ is used to realise 2D-FFT, first, the echo signal is, respectively, used to do M-point FFT in each modulation cycle T. Second, the output matrix is transposed. Finally, the L-point FFT is done in the range dimension of the transposed matrix, that is, the two-dimensional FFT processing is realised, and the processing flow is as Fig. 2 shows:

The M-point FFT is a Fourier transform of the range dimension from which distance information can be extracted. Its distance resolution is proportional to the frequency resolution of FFT. When the sampling frequency is certain, the longer the signal time is and the more sampling points are, the higher the frequency resolution is. However, the increase in the number of points will increase processing time, so a compromise choice need to be made under these circumstances which the smallest point meets resolution. Here, FFT frequency resolution is:

$$\Delta f = \frac{f_s}{M} \tag{15}$$

where f_s is the sampling frequency of A / D and M is the point of one-dimensional FFT.

The range formula is:

$$R = \frac{\mathrm{Tc}}{2B}\left(f_r - \frac{2f_0 v}{c}\right) \tag{16}$$

The range resolution is:

$$\Delta R = \frac{\mathrm{Tcf}_s}{2\mathrm{BM}} \tag{17}$$

After range-dimensional FFT, the data matrix must be transposed. As the data in RAM is sorted in a single column, and transposing means converting the address of RAM. After transposing, the

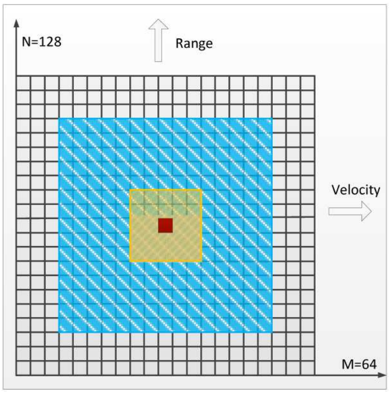

Fig. 3 *2D CA-CFAR schematic*

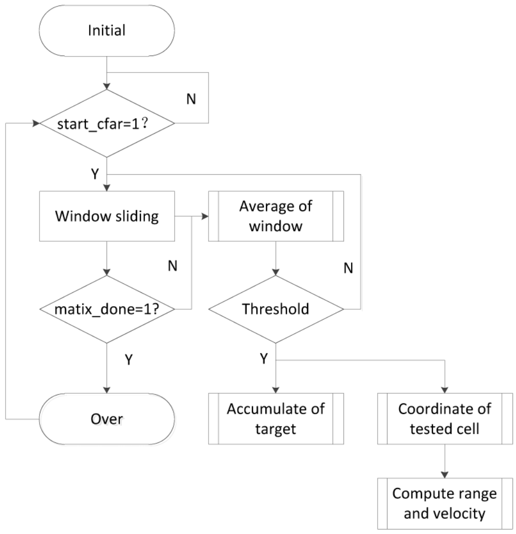

Fig. 4 *2D CA-CFAR in ZYNQ*

velocity-dimension FFT is done and the results are two-dimensional FFT, also known as Range-Doppler (R-D) graph.

The velocity formula is:

$$v = \frac{\mathrm{c}f_v}{2(f_0 + B/2)} \tag{18}$$

The velocity resolution is:

$$\Delta v = \frac{c}{2\mathrm{TL}(f_0 + B/2)} \tag{19}$$

4 Two-dimensional CA-CFAR

As of wide bandwidth of LFMCW radar and the high range resolution, so the target of automobile is expressed as multiple points on the distance dimension. In addition, because of the change of the radar angle of view, the automobile targets may be extended in the velocity dimension. Therefore, the automobile is represented as expansion target holding multiple cells in the R-D graph.

If one-dimensional CFAR is used, the reference cell can only be selected in the range dimension or the Doppler dimension where the tested cell is located, and the information of the target on the R-D graph cannot be utilised simultaneously. Furthermore, one-dimensional CFAR suffers from masking targets when dealing with multiple targets, and the length of reference window which can be selected is limited. The number of reference cell of 2D CFAR can significantly improve the estimation accuracy of background noise and reduce the estimation loss. Therefore, in order to make full use of the features of the target on the R-D graph and improve the detection effect of the target CFAR, the 2D CA-CFAR algorithm is used in this paper as shown in Fig. 3.

Table 1 Radar Parameters

Parameter	Value
f_0	24.125 GHz
T	100×10^{-6} s
B	250 MHz
f_s	1.28 MHz

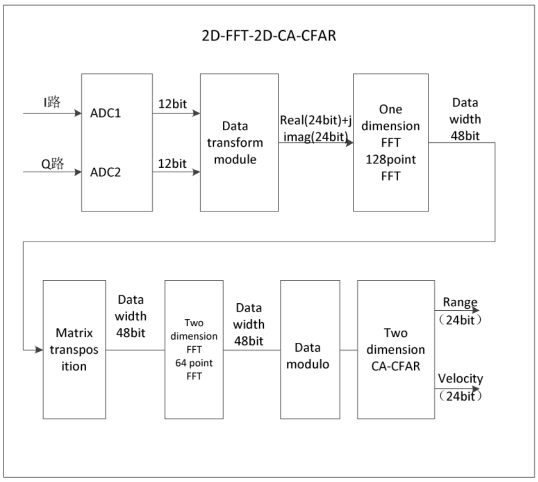

Fig. 5 *Two-dimensional FFT-two-dimensional CFAR Implementation flow on ZYNQ*

The 2D CA-CFAR adopts rectangular window. The number of the cell to be estimated for average value is n. In order to eliminate the mutual interference of adjacent cell, two cells are selected as protected units. Constant False Alarm is $P_{\mathrm{fa}} = 10^{-6}$.Threshold factor is $K_0 = n \times \left(P_{\mathrm{fa}}^{-1/n} - 1\right)$. Threshold is $Z = K_0 \times \mathrm{win\_sum}/\mathrm{ref}\_n$ (win_sum is sum of the sliding window data and ref_n is the number of cell). Finally, the target is determined by comparing the threshold with the value of the tested cell.

The implementation of 2D CA-CFAR in ZYNQ is shown in Fig. 4.

Parameters are firstly initialised when calling a 2D CA-CFAR module. The CFAR start signal is given at the halfway of the 2D-FFT calculation, after which the module enters the sliding window phase. In the sliding window phase, the sliding window boundary needs to be determined including the number of reference cells in the window, and the coordinate (i, j) of the current tested cell. After the cell tested is compared with the threshold, if the threshold value is greater than the tested cell, this point is not the target; if the tested cell is larger than the threshold, the cell is the target, at the same time the number of target is added. At this point, you can use $\mathrm{Range} = j \times \Delta R$ and $V = i \times \Delta v$ to get range and velocity. The matrix_done signal is high level if the whole two-dimensional matrix is completed.

5 Experimental verification and analysis

This experiment uses a 24 GHz LFMCW radar to illuminate the rear of a car. Radar parameters are shown in Table 1. Radar height is 0.60 m. Signal processing chip is XC7Z035-ffg676-2. Since the car has more than one scattering point, subsequent requiring clustering of the point targets. So, ZYNQ is selected, including both FPGA and ARM, which do not only a lot of parallel operations but also DSP processing. The diagram of processing flow on the hardware is shown in Fig. 5. The input of the data acquisition card is connected to I/Q output of the radar. After data accumulated for multiple cycles, data is intercepted for 8192 (sorted by column) to be converted to fixed-point format buffered in ZYNQ RAM. The 128-point FFT transformation is carried out in the first-dimension FFT module, and then the output data flow into matrix transpose module and cache data is outputted sequentially into RAM in row order. Then, data are processed by

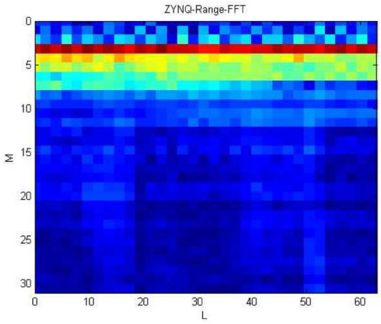

Fig. 6 *One-dimensional FFT on ZYNQ*

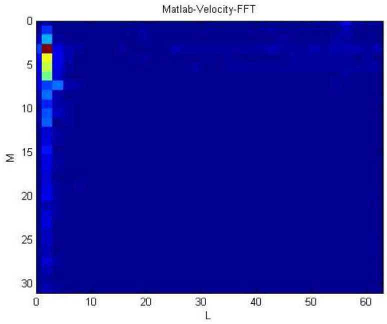

Fig. 8 *2D-FFT on ZYNQ*

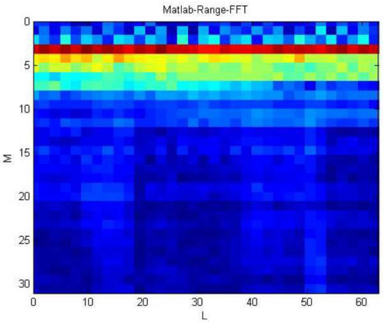

Fig. 7 *One-dimensional FFT on Matlab*

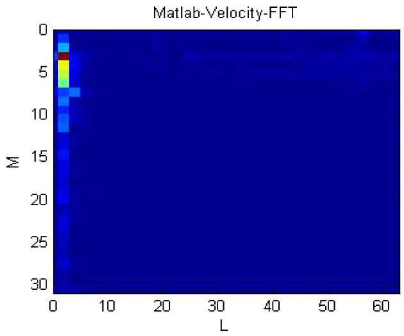

Fig. 9 *2D-FFT on Matlab*

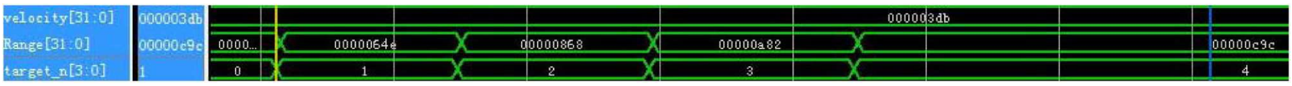

Fig. 10 *Results of 2D CA-CFAR*

the second dimensional 64-point FFT module, and the output of the complex data must be in a modulo. Finally, the 2D CA-CFAR module is used for target detection.

As data format measured uses fixed-point (24,12). The first symbol is bit. The fractional part has 12 bits. The FFT output data is 48 bits. The first 24 bits are real part, and the last 24bits are imaginary part. Due to the large amount of FFT data cannot be displayed in one diagram of online simulation, thus data being exported and then mapped in Matlab. The actual processing results of ZYNQ are shown in the figure. The one-dimensional FFT (range dimension) results are shown in Fig. 6, and the corresponding results of Matlab processing are shown in Fig. 7.

From one-dimensional results, if only one-dimensional results are obtained for the data, then after one-dimensional CFAR, the range cannot be determined. Moreover, the result is inaccurate because the energy is not enough concentrated. Therefore, we must continue to do 2D FFT processing.

After the two-dimensional FFT calculation. The actual results on ZYNQ is shown in Fig. 8 and the corresponding processing results using Matlab is shown in Fig. 9. The results are the same.

Owing to the data of 2D-FFT being complex. Before data flowing into the 2D CA-CFAR module, it must be using modulo operator. Since the maximum value of the data is changed in modulo, the width of data is changed, and data must be expanded to 32 bits.

The results of 2D CA-CFAR are shown in Fig. 10. The target number, the corresponding target velocity and the range are obtained by the conversion of fixed-point number (32, 10). Range is 64E (1.5761 m), 868 (2.1015 m), A82 (2.6269 m), and C9C (3.15 m). Velocity is 3DB (0.9638 m/s). Target number is 4 (decimal). The deviation of the results is caused by the intercept error of the fixed-point. The entire processing process takes 16 ms to meet real-time performance requirements.

6 Conclusion

In this paper, 2D FFT and 2D CA-CFAR algorithm based on ZYNQ is proposed and a LFMCW signal processing system of automotive radar is implemented. From the experiment results, it is concluded that the scheme can effectively detect moving targets and obtain high-precision information of targets velocity and range in real-time.

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