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Moving Target Detection Using The 2D-FFT Algorithm For Automotive FMCW Radars

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***Abstract*—The FMCW (frequency modulated continuous wave) automotive radar has been widely used in the advanced driving assistant system of vehicles. The basic idea of FMCW automotive radar is to obtain the range and velocity information from the beat signal. However, the information extracted from one frequency ramp will suffer from the range-velocity ambiguity problem. In this paper, several subsequent ramps have been generated to eliminate this ambiguity and a two dimensional FFT algorithm for the FMCW radar is presented. The parameters of FMCW signal are derived mathematically. An experiment in actual traffic environment is conducted and the offline raw radar data are captured by using the AWR1642BOOST. The data processed by MATLAB shows that the 2D FFT algorithm can obtain the range and velocity information of moving targets without ambiguity.**

Keywords-Automotive radar; FMCW; 2D-FFT; AWR1642BOOST

I. Introduction

Recently, the FMCW (frequency modulated continuous wave) automotive radars have been employed in various active safety applications, such as adaptive cruise control, lane change assist and pre-crash sensing [1]. Studies have shown that most traffic accidents can be avoided if drivers can realize the dangerous situations 1~2 seconds in advance and take corresponding safety measures in time [2]. Therefore, the research of automotive radar has been significantly growing in popularity in recently [3]. Automotive radar generally transmits a frequency modulated continuous signal, and the received signal is reflected from the target [4]. We can get the beat signal which can be used for range and velocity estimation of moving target by mixing the transmitted signal and the received signal. However, the range and velocity of a target cannot be simultaneously determined by single beat signal because of range-velocity ambiguity [5]. Multiple ramps must be generated to remove this ambiguity. The study of FMCW radar is mainly carried out in 24GHz and 77GHz frequency band at present. Compared to the 24GHz FMCW radar, the 77GHz FMCW radar is being studied and applied more widely in automotive radar systems, which has many advantages of high resolution, high compactness, and low cost [5]. Throughout the world, many chip manufacturers such as Infineon, NXP, and Texas Instrument have launched their own 77GHz radar chip. AWR1642 is a 77GHz FMCW radar chip of Texas Instrument which has integrated 600 MHz DSP and 200 MHz MCU. It can work in 76~77GHz and 77~81GHz frequency band so that the highest range resolution of 4cm can be achieved, and the biggest intermediate frequency bandwidth can reach 5MHz. In this paper, the evaluation board of AWR1642 chip has been used to capture the offline raw ADC data of beat signal. And then we studied the two dimensional FFT (2D-FFT) algorithm which has been applied to the range and velocity estimation of moving target.

The contents of this paper have following: in Sect. 2, we analyze the FMCW signal and the features of beat signal of moving target. In Sect. 3, we introduce the process of mathematical derivation of the 2D-FFT algorithm and acquisition of distance and velocity of moving target. We also derived some useful parameters of FMCW radar (e.g., range resolution, maximum unambiguous range). Then in Sect. 4, an experiment is carried out to verify the 2D-FFT algorithm. Finally, conclusions are given in Sect. 5.

II. FMCW Radar Equations

The basic idea in FMCW signal is to generate a linear frequency ramp [6]. This sweep in frequency is commonly referred to as a “chirp” [7]. Assume that the FMCW radar emits a sawtooth frequency modulated signal. The transmitted signal for one ramp with sweep bandwidth B and duration T between $[0,T]$ can be expressed as:

$$x(t) = A\cos(2\pi f_c t + \pi \frac{B}{T} t^2 + \varphi_0) \qquad (1)$$

where A is the amplitude of signal, f_c is the carrier frequency and φ_0 denotes the initial phase of signal. We can also define $\mu = B/T$ as the frequency slope of ramp.

The phase $\varphi_T(t)$ of transmitted signal $x(t)$ is:

$$\varphi_T(t) = 2\pi(f_c t + \frac{1}{2}\mu t^2) + \varphi_0 \qquad (2)$$

When a target with an initial range R_0 (at $t=0$) moves with a constant velocity v (assume that departing from the radar is the positive direction), the received signal that reflected from the target can be expressed as:

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$$r(t) = \alpha A\cos[2\pi f_c(t-\tau) + \pi\mu(t-\tau)^2 + \varphi_0] \quad (3)$$

where α is the gain of signal which depends on the gain of antenna, the propagated distance and the RCS of target. where $\tau = 2R(t)/c = 2(R_0 + vt)/c$ denotes the propagation delay, and c is the velocity of light.

The phase $\varphi_R(t)$ of received signal $r(t)$ is:

$$\varphi_R(t) = 2\pi[f_c(t-\tau) + \frac{1}{2}\mu(t-\tau)^2 + \varphi_0] \quad (4)$$

The phase of the beat signal by mixing the transmitted signal and received signal $\Delta\varphi(t) = \varphi_T(t) - \varphi_R(t)$ is:

$$\begin{aligned}\Delta\varphi(t) = 2\pi[(&\frac{2f_c v}{c} + \frac{2\mu R_0}{c} - \frac{4\mu R_0 v}{c^2})t + \\ &(\frac{2\mu v}{c} - \frac{2\mu v^2}{c^2})t^2 + \frac{2f_c R_0}{c} - \frac{2\mu R_0^2}{c^2}]\end{aligned} \quad (5)$$

From above analysis, the beat signal of moving target $A_m\cos(\Delta\varphi(t))$ is also a linear frequency modulated signal, where A_m is the amplitude of the beat signal. And we can set A_m to 1 for convenience of following analysis, signal attenuation is not considered in other words.

From (5), we can get the bandwidth of the beat signal:

$$B_m = \frac{4Bv}{c} - \frac{4Bv^2}{c^2} \approx \frac{4Bv}{c} \quad (6)$$

The carrier frequency of the beat signal is:

$$\begin{aligned} f_m &= \frac{2f_c v}{c} + \frac{2\mu R_0}{c} - \frac{4\mu R_0 v}{c^2} \\ &\approx f_d + f_\tau \end{aligned} \quad (7)$$

where f_d is the doppler frequency, and $f_\tau = 2\mu R_0/c$ denotes the frequency produced by the range between the target and radar. And the phase of the beat signal is represented by:

$$\begin{aligned}\varphi_m &= 2\pi(\frac{2f_c R_0}{c} - \frac{2\mu R_0^2}{c^2}) \\ &\approx \frac{4f_c R_0 \pi}{c}\end{aligned} \quad (8)$$

When the duration T is in the order of microseconds, $t^2 \ll T$. Therefore, we can neglect the term associated with t^2 in (5). Then, the expression of the beat signal can be led to:

$$\begin{aligned} s_{BF}(t) &= \cos(\Delta\varphi(t)) \\ &= \cos\left\{2\pi\left[(f_d + f_\tau)t + \frac{2f_c R_0}{c}\right]\right\} \end{aligned} \quad (9)$$

The complex representation of the beat signal can be written in the follows:

$$S_{BF}(t) = e^{j2\pi\left[(f_d+f_\tau)t + \frac{2f_c R_0}{c}\right]} \quad (10)$$

The discrete form of (10) can be expressed as:

$$S_{BF}(nT_s) = e^{j2\pi\left[(f_d+f_\tau)T_s n + \frac{2f_c R_0}{c}\right]} \quad (11)$$

where T_s is the sampling interval, and n is the sampling point.

III. DETECTION BASED ON THE 2D-FFT ALGORITHM

In factual FMCW radar system, the RF front-end will generate M frequency ramps after another like shown in Fig. 1, and a set of these chirps form a "frame" [6]. The T_c in Fig. 1 denotes the ramp repetition interval and T is the ramp time of each chirp. The A in Fig. 1 is the time between the end of previous chirp and start of next chirp, the B denotes the time from the start of the ramp when the ADC starts sampling the data, and the C means the ADC sampling time of every chirp.

The resulting beat signal can be expressed as:

$$S_{BF}(t) = \sum_{m=0}^{M-1} e^{j2\pi\left[\left(f_d + f_\tau + \frac{2\mu v T_c M}{c}\right)t + \frac{2f_c(R_0 + vT_c m)}{c}\right]} \quad (12)$$

The frequency increase caused by the movement of target across different ramps can be neglected, because the movement during the measurement is short compared to the distance R_0. The beat signal (12) will be sampled with a sample rate $f_s = 1/T_s$ during each ramp, and it can be represented by:

$$S_{BF}(nT_s) = e^{j4\pi\frac{f_c R_0}{c}} \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} e^{j2\pi\left[(f_d+f_\tau)T_s n + \frac{2f_c v T_c m}{c}\right]} \quad (13)$$

where N is the number of sample points in each ramp.

And a Fourier transformation of (13) is performed for each ramp and can be expressed as:

$$S_{BF,1D}(m,k) = e^{j4\pi\frac{f_c R_0}{c}} \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} e^{j4\pi\frac{vT_c f_c m}{c}} \cdot e^{j2\pi\left[(f_d+f_\tau)T_s n - \frac{kn}{N}\right]} \quad (14)$$

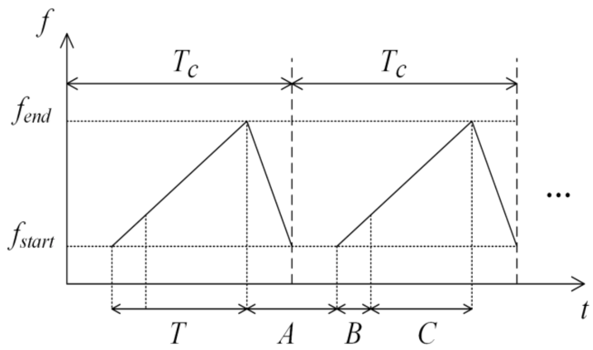

Figure 1. FMCW signal model

The peak of the Fourier spectrum $|S_{BF,1D}(m,k)|$ contains the range and velocity information of target, and it will appear at the following position:

$$k = (f_d + f_\tau)T_s N \tag{15}$$

Because of $f_d \ll f_\tau$, we can obtain the rough information of the range after the first FFT.

In the second FFT, the Fourier transformation is performed for each range unit and represented by:

$$S_{BF,2D}(l,k) = e^{j4\pi\frac{f_c R_0}{c}} \cdot \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} e^{j4\pi\frac{vT_c f_c m}{c}} \cdot e^{j2\pi\left[(f_d+f_\tau)T_s n - \left(\frac{kn}{N}+\frac{lm}{M}\right)\right]} \tag{16}$$

Reordering (16) leads to:

$$S_{BF,2D}(l,k) = e^{j4\pi\frac{f_c R_0}{c}} \cdot \sum_{m=0}^{M-1} e^{j4\pi\frac{vT_c f_c m}{c}} \cdot \left[\sum_{n=0}^{N-1} e^{j2\pi\left[(f_d+f_\tau)T_s n - \frac{kn}{N}\right]}\right] \cdot e^{-j2\pi\frac{lm}{M}} \tag{17}$$

Likewise, the peak of the spectrum $|S_{BF,2D}(l,k)|$ attains the information of velocity and will appear at:

$$l = \frac{2f_c v T_c M}{c} = f_d T_c M \tag{18}$$

And we can obtain the more accurate range information of target after acquiring the information of velocity from the second FFT.

Next, the expressions of some important parameters of FMCW radar will be derived mathematically. The maximum doppler frequency must meet the following constraint in order to fulfill the sampling theorem.

$$f_{d,\max} < \frac{1}{2T_c} \tag{19}$$

Therefore, the maximum unambiguous velocity can be derived:

$$v_m = \frac{c \cdot f_{d,\max}}{2f_c} = \frac{\lambda}{4T_c} \tag{20}$$

where λ is the wavelength of the electromagnetic wave. And the velocity resolution is determined by the overall observation time T_c as following:

$$\Delta v = \frac{\lambda}{2MT_c} \tag{21}$$

The range resolution is related to the sweep bandwidth B, but there is also a constraint of sampling time.

$$\Delta R = \frac{c}{2B_s} = \frac{cf_s}{2\mu N} \tag{22}$$

Figure 2. Top view of AWR1642BOOST

where $B_s = \mu N / f_s$ is the sampling bandwidth of the FMCW radar. And the maximum unambiguous range is determined by the maximum beat frequency $f_{BF,\max}$.

$$R_{\max} = \frac{c}{2\mu} \cdot f_{BF,\max} \tag{23}$$

IV. Experiment And Measument Results

The 2D-FFT algorithm will be verified through an experiment implemented in actual traffic environment in this section. The AWR1642BOOST is the evaluation board version of AWR1642 chip and it has an antenna array of 2 transmitters and 4 receivers (see in Fig. 2). We need the offline raw radar data for the sake of verifying the algorithm in MATLAB, and AWR1642 chip has provided this ability because there is a data cube memory (768KB) which can save the sampled data of the beat signal. The evaluation board also has a UART port that can be used to output the raw data in memory to the host PC and input the control message to the chip.

We only used one transmitter and one receiver in our experiment because there is a constraint of size of the data cube memory. The designed radar system parameters are given in Table I.

TABLE I. Radar System Parameters

Start frequency	Ramp time	Frequency slope	Chirp time
76 GHz	58 μs	8 $MHz / \mu s$	61 μs
Sample rate	Number of Chirps	Frame time	Samples per chirp
5 MHz	128	30 ms	256

The measurement performance of our FMCW radar is computed and shown in Table II. The relationship between the maximum beat frequency and the sample rate is $f_{BF,\max} = 0.9 \times f_s$ for our FMCW radar [7].

TABLE II. The Performance of Radar

v_m	Δv	$R_{\max}$	ΔR
58.23km/h	0.91km/h	84.375m	0.366m

Figure 3. The scenario of experiment

The scenario of the experiment is shown in Fig. 3, where the static strong reflectors contain the lamp post and dustbin with metal. The AWR1642BOOST is mounted on a tripod and connected with a laptop with an USB cable. But note that the targets (i.e. car and pedestrians) in Fig. 3 is not corresponding to the detected target of the measured data. For the beginning, the measured samples are multiplied with a blackman window and 512 point the first FFT with zero-padding is calculated for each chirp. The result of the first FFT for collected data is shown in Fig. 4. Then we have subtracted the mean value of the result of the first FFT before performing the second FFT because we only care about the moving target in our experiment. And for the calculation of doppler spectrum, a blackman window is also employed and 256 point the second FFT with zero-padding is performed. The result of the second FFT for collected data is shown in Fig. 5. And the imaging result of collected data is presented in Fig. 6. The strongest detected target is a car approaching to the radar, we also detect a man who is riding an electric bike away from the radar, and the pedestrians with low speed are also detected by the radar.

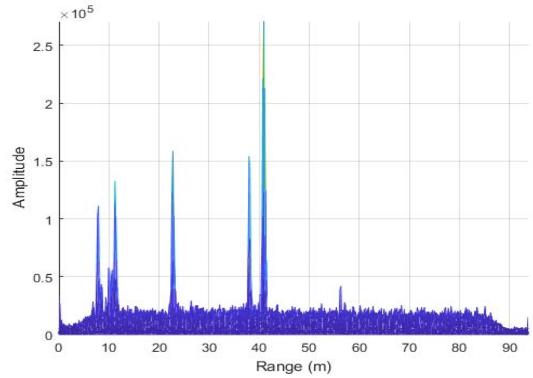

Figure 4. First FFT plot for collected data

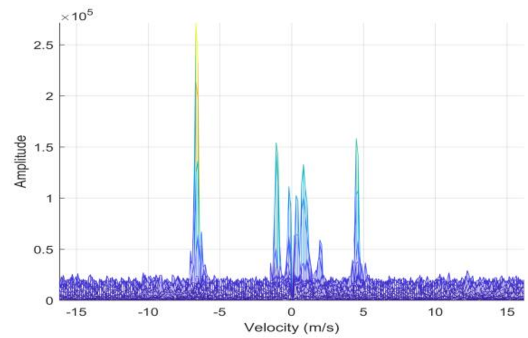

Figure 5. Second FFT plot for collected data

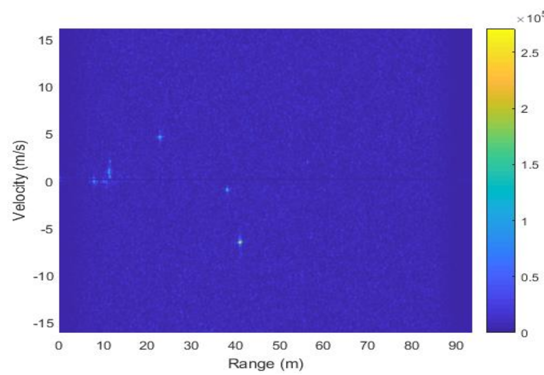

Figure 6. The imaging result of 2D-FFT

V. Conclusion

In this paper, we have presented the effectivity of using the two dimensional FFT algorithm and FMCW radar to detect the range and velocity for the moving targets. The FMCW signal model is built and we derive the relationship between FMCW radar parameters mathematically. The data collected from moving cars and pedestrians are processed by the 2D-FFT algorithm. In the future, the study of the clutter removal and related experiments will be carried out.

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