24 GHz FMCW Radar Sensor Algorithms for Car Applications

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Abstract: *The frequency modulation continuous wave (FMCW) technique is widely used in radar sensor systems with the purpose to prevent vehicle collisions and in other safety driving systems. In this paper, we consider the signal detection algorithm based on linear FMCW (LFMCW) technique to define the relative velocity of the target vehicle. Additionally, we define the distance between the subject and target vehicles. We present simulation results for LFMCW radar sensor system.*

1. Introduction

In the present paper, we consider the linear frequency modulation continuous wave (LFMCW) radar sensor employed by safety driving systems. The relative velocity and distance between the subject and target vehicles are the main parameters of any safety driving system. Simple continuous wave radar sensor system can determine the velocity of the target vehicle using the Doppler effect, and can not determine the distance from the subject vehicle to the target vehicles. LFMCW radar sensor system can solve this problem. The general modulation scheme employed by LFMCW is the linear frequency modulation (LFM) using the transmit frequency with a triangular waveform (see Fig. 1), where B is the bandwidth, T_m

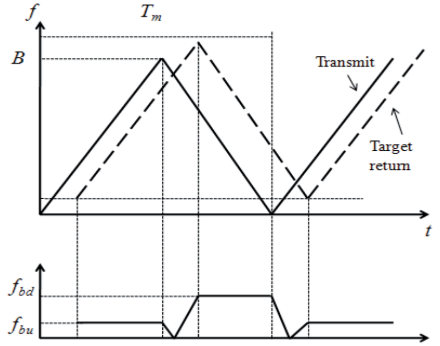


Figure 1. The triangular waveform of LFMCW radar sensor system.

is the modulation time, f_c is the carrier frequency, f_{bu} is the up beat frequency, and f_{bd} is the down beat frequency.

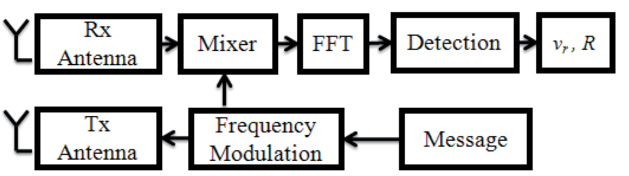


Figure 2. Structure of LFMCW radar sensor system.

Fig. 2 shows the typical structure of LFMCW radar sensor system. The frequency modulated signal is sent by the transmit antenna. The transmitted signal is reflected from the target vehicles. The reflected signal comes in at the receive antenna. The target return signal is multiplied by the transmitted signal. Difference in frequency between the transmitted and target return signals can be obtained using the mixer. The difference between frequencies is called the beat frequency. The up and down beat frequencies are distinguished using the Fourier transform (FT) at the mixer output. In the case of stationary target vehicle, the beat frequency is the constant value. However, if the target vehicle is moving, there is the Doppler effect and the beat frequency is changed. To detect the target vehicle we use the constant false alarm rate (CFAR) processor. Using the beat frequencies, we can determine the range *R,* i.e. the distance between the subject and target vehicles, and the relative velocity V_r between the subject and target vehicles in the following form

$$R = \frac{c(f_{bu} + f_{bd})T_m}{8B}, \tag{1}$$

$$V_r = \frac{c(f_{bd} - f_{bu})}{4f_c}, \tag{2}$$

where c is the speed of light. The performance of FMCW radar sensor system is a function of the up and down beat frequencies.

2. LFMCW Radar Sensor System Model

The sinusoidal transmitted signal can be written in the following form

$$S_T = \sin(\varphi_T(t)). \tag{3}$$

The instantaneous transmitted phase $\varphi_T(t)$ frequency can be defined as

$$\varphi_T(t) = 2\pi \int_0^t f_T(t)dt\,. \tag{4}$$

The instantaneous transmitted frequency $f_T(t)$ frequency can be written as

$$f_T(t) = \begin{cases} f_c + \dfrac{B}{0.5T_m}t, \; 0 < t < 0.5T_m & (5) \\ f_c - \dfrac{B}{0.5T_m}t, \; 0.5T_m < t < T_m\;. & (6) \end{cases}$$

Consider rising slope case. Substituting (4) and (5) into (3), the sinusoidal transmitted signal can be presented in the form

$$S_T(t) = \sin\left[2\pi\left(f_c t + \frac{B}{T_m}t^2\right)\right]. \tag{7}$$

The target return signal can be written as

$$S_R(t) = \sin(\varphi_R(t)) = \sin\left\{2\pi\left[f_c(t-\tau) + \frac{B}{T_m}(t-\tau)^2\right]\right\}, \tag{8}$$

where τ is the delay between the transmitted and target return signals [1].
The transmitted signal is multiplied by the target return signal in the mixer. Using the following trigonometric identity

$$S_T(t)S_R(t) = -\frac{1}{2}\cos(\varphi_T + \varphi_R) + \frac{1}{2}\cos(\varphi_T - \varphi_R), \tag{9}$$

we see that the first term in (9) is absent at the low pass filter output. The second term in (9) can be expressed as

$$S_{MU}(t)=\frac{1}{2}\cos\left(\varphi_T-\varphi_R\right)=\frac{1}{2}\cos\left\{2\pi\left[f_c t+\frac{B}{T_m}t^2-f_c(t-\tau)-\frac{B}{T_m}(t-\tau)^2\right]\right\}$$
$$=\frac{1}{2}\cos\left[2\pi\left(f_c\tau+\frac{2B}{T_m}t\tau-\frac{B}{T_m}\tau^2\right)\right]. \tag{10}$$

The last term $\frac{B}{T_m}\tau^2$ in (10) can be neglected owing to $\frac{\tau}{T_m} << 1$.

In the case of the stationary target vehicle, the delay τ is expressed as follows

$$\tau=\frac{2R}{c}. \tag{11}$$

If the target vehicle is moving, the delay τ is a function of the relative velocity. In this case, the delay τ is determined as

$$\tau=\frac{2(R-V_r t)}{c}. \tag{12}$$

In the case of the receding target vehicle, the delay τ is expressed as follows

$$\tau=\frac{2(R+V_r t)}{c}. \tag{13}$$

Substituting (12) into (10), the signal at the mixer output can be written as

$$S_{MU}(t)\approx\frac{1}{2}\cos\left\{2\pi\left[\frac{2R}{c}f_c+\left(\frac{4BR}{T_m c}-\frac{2V_r}{c}f_c\right)t-\frac{4BV_r}{T_m c}t^2\right]\right\}. \tag{14}$$

The last term in (14) known as the range-Doppler coupling can be dropped. Finally, in the case of $0<t<0.5T_m$, the signal at the mixer output can be presented in the following form

$$S_{MU}(t)\approx\frac{1}{2}\cos\left\{2\pi\left[\frac{2R}{c}f_c+\left(\frac{4BR}{T_m c}-\frac{2V_r}{c}f_c\right)t\right]\right\}. \tag{15}$$

In the case of falling slope case, the signal at the mixer output takes the following form

$$S_{MD}(t)\approx\frac{1}{2}\cos\left\{2\pi\left[\frac{2R}{c}f_c-\left(\frac{4BR}{T_m c}+\frac{2V_r}{c}f_c\right)t\right]\right\}. \tag{16}$$

From the (15) and (16), the up beat and down beat frequency can be defined,

$$f_{bu}=\frac{4BR}{T_m c}-\frac{2V_r}{c}f_c, \tag{17}$$

$$f_{bd}=\frac{4BR}{T_m c}+\frac{2V_r}{c}f_c, \tag{18}$$

respectively. The first term in (17) and (18) is the beat frequency when the target vehicle is stationary. The second term in (17) and (18) is known as the Doppler frequency occuring when the target vehicle is moving. We can see that the up and down beat frequency are determined by adding the frequency of the stationary target vehicle and Doppler frequency, and (1) and (2) can be obtained by combining (17) and (18).

3. OS-CFAR

The noise and clutter power affect on detection performance. In practice, the interference power is often variable. To provide a predictable detection and false alarm probability behaviour setting of the threshold is based on the interference power. We employ the CFAR detection technique, namely, the order statistic CFAR (OS-CFAR) that is one of popular techniques. OS-CFAR is robust with respect to target masking phenomenon in comparison with cell averaging CFAR technique [4].

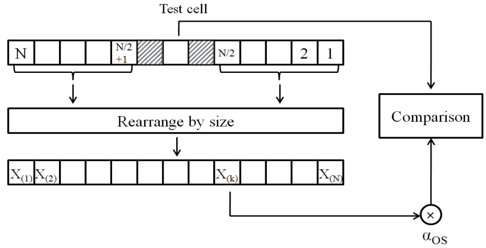


Figure 3. OS-CFAR.

OS-CFAR arranges the reference window data samples $\{x_1, x_2, \cdots, x_N\}$ to form a new sequence according to the interference power denoted by $\{x_{(1)}, x_{(2)}, \cdots, x_{(k)}, \cdots, x_{(N)}\}$. The kth element of the ordered sample is called the kth order statistics, $x_{(k)}$. The number k is usually equal to $0.75N$ [2]. The threshold is set by kth order statistic as follows

$$T = \alpha_{OS} x_{(k)} \ . \tag{14}$$

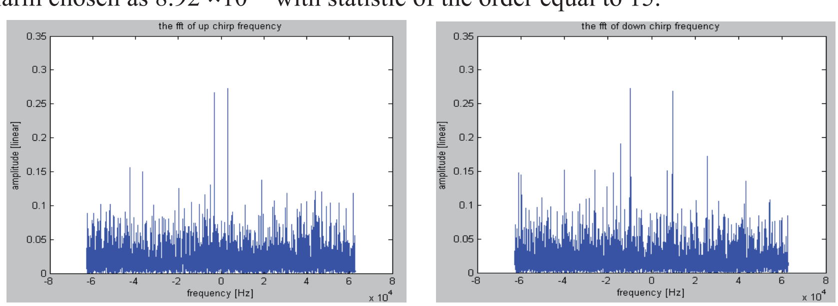
The interference power is estimated by one data sample. The threshold depends on a total set of data, since all samples are rearranged in order. In the case of OS-CFAR, a relationship between the probability of false alarm and scale-factor α_{OS} is defined in the following form

$$P_{FA} = \frac{N!(\alpha_{OS} + N + k)!}{(N - k)!(\alpha_{OS} + N)!} \ , \tag{15}$$

where the scale-factor α_{OS} is integer.

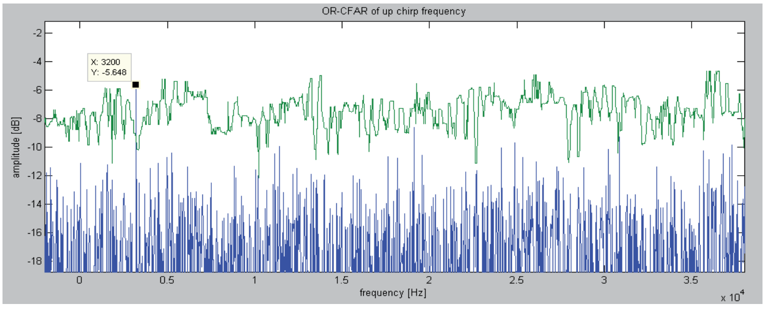
4. Simulation

We carry out a simulation using MATLAB under the condition that a single target vehicle is approaching from the rear with the relative velocity equal to 20 m/s and 50 m away from the subject vehicle. The radar carrier frequency is 24 GHz, the bandwidth is 600 MHz, and the modulation time is 0.0625 sec. To achieve the 0.25 m range resolution and velocity resolution equal to 0.2 m/s, the system requires theoretically the bandwidth 600 MHz and modulation time 0.0625 sec [3]. Fig. 4 shows the up and down chirp target return signals at the mixer output where the noise is distributed exponentially. OS-CFAR scheme is applied to the signal at the mixer output with 20 reference cells, 3 guard cells for each side and the probability of false alarm chosen as 8.92×10^{-4} with statistic of the order equal to 15.

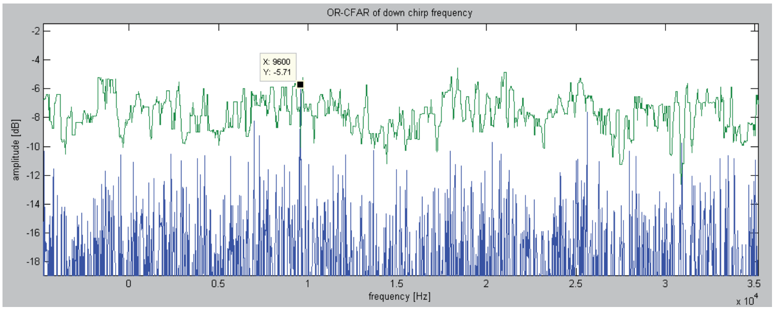


(a) (b)

Figure 4. The target return signals for the multi-target case with interference; (a) the up chirp signal; (b) the down chirp signal.



(a)



(b)

Figure 5. OS-CFAR; (a) the up chirp signal; (b) the down chirp signal.

As we can see from Fig. 5, the detected up and down beat frequency of the target vehicle are 3200 Hz and 9600 Hz, respectively. Using the detected beat frequencies, the relative velocity and range can be defined by (1) and (2).

5. Conclusions

In this paper, the safety driving system is employed using the proposed 24 GHz LFMCW radar sensor system. The LFMCW radar sensor system with the target return signal processing to define the relative velocity and the range of the target vehicle is introduced. For the target return signal detection problem, an adaptive threshold detection method based on CFAR technique is analyzed. The theoretical analysis of the safety driving system is expanded by the simulation under pratical conditions. The simulation results show how the system can detect the target vehicle that is approaching to the subject vehicle, and define the beat frequencies by applying the presented OS-CFAR technique. The obtained beat frequencies are used to define the relative velocity and range of the target vehicle. The OS-CFAR detection technique is confirmed by simulation.

Acknowledgements

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