Method to improve degraded range resolution due to non-ideal factors in FMCW radar

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Abstract: This paper reports a method to improve a degraded range resolution for FMCW radar. The proposed post-processing method can achieve an improved range resolution without increasing a signal bandwidth by eliminating factors that can degrade the range resolution based on the non-negative least-squares method. For an FMCW radar adopting the post-processing method with the center frequency of 76.5 GHz and the signal bandwidth of 200 MHz, simulation results show that the degraded range resolution of 160 cm is improved to 70 cm, and measurements show that two corner reflectors with the radar cross section of 10 dBsm located at 70 cm range intervals can be distinguished.

Keywords: FMCW, radar, range resolution, signal bandwidth, non-negative least-squares method

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

A frequency-modulated continuous wave (FMCW) radar is a device that outputs object information such as range, velocity, and angle through radar signal processing [1]. Range resolution to detect adjacent objects separately is one of the important performance parameters of FMCW radar [2]. The theoretical range resolution can be calculated with the light velocity and signal bandwidth. However, the actual range resolution is degraded due to non-ideal factors in FMCW radar. Non-ideal factors include the reduced effective modulation bandwidth due to time-of-flight delays, the increased main-lobe null-to-null bandwidth when FFT windows are applied, and non-linearity of frequency sweeps [3, 4, 5]. Various studies have been reported to improve range resolution, such as increasing bandwidth [6], using triangular sweep signal [7], over-sampling [8], and removing aliasing effects [9]. However, since these methods cannot suppress non-ideal effects on range resolution, range resolution can be further improved by compensating for non-ideal factors. In this paper, post-processing based on the non-negative least-squares method (LSM) is applied to compensate non-ideal factors and improve range resolution without increasing signal bandwidth.

2 Range resolution improvement for FMCW radar

Fig. 1 shows the time-frequency plot of a sawtooth sweep signal which is mainly used in FMCW radar. When continuous chirp signals with a chirp length t_m and a modulation bandwidth Δf are transmitted from FMCW radar, an echo signal reflected from objects is received after a time-of-flight delay t_{delay} . By mixing a received signal with a transmitted signal, a beat signal, which has a frequency difference f_{beat} between two signals, can be obtained and a range can be calculated.

However, there are several non-ideal factors that degrade the range resolution, such as reduced effective modulation time t_{meff} or bandwidth Δf_{eff} due to t_{delay} , nonlinearity in the frequency sweep, and FFT window function effects. First, as shown in Fig. 1, the effective modulation time to find f_{beat} is t_{meff} , which is reduced by t_{delay} from t_m , while the effective modulation bandwidth is reduced from

Fig. 1. Time frequency plot of sawtooth sweep signal for FMCW radar

Δf to Δf_{eff} . Therefore, the range resolution ΔR given by Eq. (1) is degraded by the ratio of t_{meff} to t_m [4]:

$$\Delta R = \frac{c}{2\Delta f_{eff}} = \frac{c}{2\Delta f \left(\frac{t_{meff}}{t_m} \right)}, \quad (1)$$

where c is the light velocity. Next, nonlinearity in frequency sweep means that chirp distortion or discontinuity occurs due to noise or the performance limitations of waveform generators. If the slope of a chirp signal is not linear, it is difficult to distinguish between multiple objects because beat frequency components corresponding to object positions cannot be accurately predicted. Finally, adopting FFT windows in the time domain for range FFT lowers the side-lobe level in the frequency domain, but it broadens the null-to-null bandwidth of the main-lobe spectra [1]. In the frequency domain, the broadened null-to-null bandwidth degrades ΔR because multiple beat frequency components are overlapped and difficult to distinguish. To improve ΔR without increasing Δf_{eff} , the influence of these non-ideal factors should be reduced.

Fortunately, the reduced t_{meff} , nonlinearity in the frequency sweep, and FFT window function effects can be quantified through design processes and module measurements. Therefore, a high-resolution range profile can be obtained by removing predictable and quantifiable non-ideal factors from measured beat signals. Fig. 2 shows a block diagram of the proposed radar signal processing with post-processing after the conventional range FFT to compensate for degraded ΔR in FMCW radar. The post-processing can be implemented by solving an equation given in Eq. (2) using the LSM [10]:

$$\arg \min_{\mathbf{x}} \|\mathbf{D}\mathbf{x} - \mathbf{y}\|_2^2 = \left\| \begin{bmatrix} s_1 & 0 & \cdots & 0 \\ \vdots & s_1 & & \vdots \\ s_L & \vdots & \ddots & 0 \\ 0 & s_L & & s_1 \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & 0 & s_L \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{M-1} \\ x_M \end{bmatrix} - \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_{M-1} \\ y_M \end{bmatrix} \right\|, \quad (2)$$

where $\mathbf{D}$ is the correlation matrix, $\mathbf{x}$ is the estimated discrete range profile, and $\mathbf{y}$ is the range FFT result of measured echo signals at the baseband. $\mathbf{s} = [s_1 \ s_2 \ \cdots \ s_L]^T$

Fig. 2. Block diagram of radar signal processing

is the normalized range FFT result within null-to-null bandwidth L of an estimated beat signal for one object detection that reflects predictable non-ideal effects. The correlation matrix $\mathbf{D}$ consists of $\mathbf{s}$ shifted by one range bin for each column. Here, M is the number of range bins. By solving Eq. (2) based on the LSM, the measured range FFT result is decomposed into peak range bins in $\mathbf{x}$ corresponding to object positions and waveform spectra in $\mathbf{D}$ reflecting degradation information in the frequency domain. Because power spectra are non-negative variables, the non-negative LSM can be used to obtain $\mathbf{x}$ in Eq. (2) to mitigate overfitting due to random noise.

3 Simulation and measurement results

To verify the improvement in the range resolution with the proposed post-processing method, radar signal processing was performed using MATLAB. For radar signal processing based on Eq. (2), $\mathbf{y}$ and $\mathbf{D}$ were generated considering radar parameters and non-ideal factors, and $\mathbf{x}$ was estimated using the non-negative LSM from $\mathbf{y}$ and $\mathbf{D}$. To analyze only the effect on ΔR , it is assumed that objects are stationary. A time-domain beat signal y_1 for one object with non-linearity noise [4] is given by

$$y_1(t) = c_0 \cos 2\pi \left\{ \left(f_0 + \frac{\Delta f}{2} \right) \left(\frac{2R}{c} \right) + \frac{\Delta f}{2t_m} \left(\frac{2R}{c} \right)^2 - \frac{\Delta f}{t_m} \left(\frac{2R}{c} \right) t \right. \\ \left. + \frac{A_n}{2\pi f_n} \left[\cos 2\pi f_n \left(t - \frac{2R}{c} \right) - \cos 2\pi f_n t \right] \right\} \quad (3)$$

where c_0 is the signal amplitude, c is the light velocity, f_0 is the center frequency, Δf is the modulation bandwidth, R is the range between an object and the radar, t_m is the chirp length, A_n is the amplitude noise component, and f_n is the frequency noise component. The radar parameters for beat signal generation in Eq. (3) are f_0 of 76.5 GHz, Δf of 200 MHz, R of 50 m, A_n of 0.01, and f_n of 1 MHz. To get the range FFT result, a beat signal in the time domain in Eq. (3) is sampled and transformed into the frequency domain with a sampling frequency f_s of 10 MHz, a FFT size N_{FFT} of 2048, and a Hann window. Note that applying a Hann window doubles the null-to-null bandwidth and ΔR . Here, $\mathbf{s}$ and $\mathbf{y}$ in Eq. (2) can be generated from Eq. (3) with the range parameters and range FFT. The $\mathbf{s}$ is the

Fig. 3. Simulated probabilities of two-object detection (a) Conventional range detection (b) Proposed range detection

Fig. 4. Measurement environment and results (a) Radar module (b) Radar module and two corner reflectors (c) Range FFT (dotted) and post-processing (lined) outputs

normalized main-lobe magnitude components of a beat signal for one object without additive white Gaussian noise (AWGN), while y can be generated by summing the beat signals for each object with AWGN. For simulations without and with the application of the proposed post-processing method, the range interval ΔR_i between two objects was varied from 150 to 200 cm and from 50 to 100 cm with 10 cm intervals, respectively, and the SNR was varied from -20 to 40 dB with 1 dB intervals. Threshold values were set to satisfy the probability of false alarm (P_{FA}) of 10^{-3} for each SNR [1].

Fig. 3 shows the simulated detection probabilities (P_D) for distinguishing and detecting two objects for each ΔR_i . Fig. 3(a) shows the P_D for the conventional range FFT, while Fig. 3(b) shows the P_D when the proposed post-processing method is applied after the range FFT to compensate for the deterioration of the range resolution. When the P_D of 0.9 and P_{FA} of 10^{-3} required in a typical radar system are satisfied [8], the ΔR is 160 cm due to the Hann window effect and nonlinearity noise as shown in Fig. 3(a); however, the improved ΔR becomes 70 cm as a result of post-processing based on the non-negative LSM as shown in Fig. 3(b). Note that the theoretical ΔR is 75 cm with the signal bandwidth of 200 MHz according to Eq. (1).

Fig. 4 shows the measurement environment and results. Fig. 4(a) shows the 77 GHz radar module, which was implemented using a NXP transceiver chipset (MR2001TX/RX/VC), NXP MCU (MPC 5775K), and planar antennas. Fig. 4(b) shows the measurement environment. One corner reflector was located at 1.3 m and the other corner reflector was located with ΔR_i to verify the ΔR in Fig. 3(b). The two corner reflectors were designed to meet a radar cross section (RCS) of 10 dBsm at 77 GHz. Fig. 4(c) shows the range FFT (dotted) and post-processing (lined) outputs of the measured beat signals with the SNR of 21 dB, when ΔR_i is 30, 70, 110, and 150 cm, respectively. When ΔR_i was less than 150 cm, the beat frequency components corresponding to two objects overlapped in the range FFT result. However, when ΔR_i was 70 cm or more, by applying the post-processing to the range FFT result, the frequency components could be distinguished and appeared at each range bin with an average error of 31 cm. Note that the range bin resolution is 13.8 cm.

4 Conclusion

The proposed post-processing method is applied to range FFT results to improve a degraded the range resolution ΔR due to non-ideal factors in FMCW radar. The proposed method derives a high-resolution range profile in frequency range from a measured beat signal and predicted beat signals reflecting deterioration information, based on the non-negative LSM. To verify the proposed method, beat signals for two objects with the range interval ΔR_i of 70 cm were measured from the radar module with f_0 of 76.5 GHz and Δf of 200 MHz. The two objects with ΔR_i of 70 cm, which are difficult to distinguish by conventional range detection, can be distinguished and detected by applying the proposed post-processing method.

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