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

References

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 $\Delta f$ are transmitted from FMCW radar, an echo signal reflected from objects is received after a time-of-flight delay $t_{\text{delay}}$. By mixing a received signal with a transmitted signal, a beat signal, which has a frequency difference $f_{\text{beat}}$ 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 $t_{\text{meff}}$ or bandwidth $\Delta f_{\text{eff}}$ due to $t_{\text{delay}}$, non-linearity in the frequency sweep, and FFT window function effects. First, as shown in Fig. 1, the effective modulation time to find $f_{\text{beat}}$ is $t_{\text{meff}}$, which is reduced by $t_{\text{delay}}$ from $t_m$, while the effective modulation bandwidth is reduced from
Δf to Δf_{eff}. Therefore, the range resolution $\Delta R$ given by Eq. (1) is degraded by the ratio of $t_{meff}$ to $t_m$ [4]:

$$\Delta R = \frac{c}{2\Delta f_{eff}} = \frac{c}{2\Delta f\left(\frac{t_{meff}}{t_m}\right)},$$  \hspace{1cm} (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 $\Delta R$ because multiple beat frequency components are overlapped and difficult to distinguish. To improve $\Delta R$ without increasing $\Delta f_{eff}$, 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 $\Delta R$ in FMCW radar. The post-processing can be implemented by solving an equation given in Eq. (2) using the LSM [10]:

$$\arg \min_x \|Dx - y\|_2^2 = \begin{bmatrix} s_1 & 0 & \cdots & 0 \\ \vdots & s_1 & \ddots & \vdots \\ s_L & \vdots & \ddots & 0 \\ 0 & s_L & \cdots & s_1 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & s_L \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{M-1} \\ x_M \end{bmatrix} - \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_{M-1} \\ y_M \end{bmatrix},$$  \hspace{1cm} (2)$$

where $D$ is the correlation matrix, $x$ is the estimated discrete range profile, and $y$ is the range FFT result of measured echo signals at the baseband. $s = [s_1 \ s_2 \ \cdots \ s_L]^T$
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 $D$ consists of $s$ 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 $x$ corresponding to object positions and waveform spectra in $D$ reflecting degradation information in the frequency domain. Because power spectra are non-negative variables, the non-negative LSM can be used to obtain $x$ 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), $y$ and $D$ were generated considering radar parameters and non-ideal factors, and $x$ was estimated using the non-negative LSM from $y$ and $D$. To analyze only the effect on $\Delta R$, 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

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

(3)

where $c_0$ is the signal amplitude, $c$ is the light velocity, $f_0$ is the center frequency, $\Delta f$ 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, $\Delta f$ 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 $\Delta R$. Here, $s$ and $y$ in Eq. (2) can be generated from Eq. (3) with the range parameters and range FFT. The $s$ is the
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 $\Delta R_i$ 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 $\Delta R_i$. 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 $\Delta R$ is 160 cm due to the Hann window effect and nonlinearity noise as shown in Fig. 3(a); however, the improved $\Delta R$ 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 $\Delta R$ 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 $\Delta R_i$ to verify the $\Delta R$ 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 $\Delta R_i$ is 30, 70, 110, and 150 cm, respectively. When $\Delta R_i$ was less than 150 cm, the beat frequency components corresponding to two objects overlapped in the range FFT result. However, when $\Delta R_i$ 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 $\Delta R$ 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 $\Delta R_i$ of 70 cm were measured from the radar module with $f_0$ of 76.5 GHz and $\Delta f$ of 200 MHz. The two objects with $\Delta R_i$ 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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