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Fast communication

High-resolution velocity estimation and range profile analysis of moving target for pulse LFM UWB radar

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ABSTRACT

A high-resolution estimation of velocity and range profile (HREVRP) method is studied to yield both high-resolution radial velocity and range profile of slowly moving target for pulse linear frequency modulation (LFM) ultra-wideband (UWB) radar. Two-dimensional projection discrete Fourier transform (2-DPDFT) is utilized to estimate the velocity. The range profile is then obtained by compensating its motion and spread with this velocity estimate. In addition, a range of the velocities is derived based on velocity ambiguity and corresponding phase restriction. The proposed method does not require any initial velocity estimation and focusing matrices construction. Besides, it has superior performance of velocity estimation compared with conventional techniques, especially at low signal-to-noise ratio (SNR) levels. The simulations validate the effectiveness of the method.

1. Introduction

UWB radar, whose fractional bandwidth is not less than 25% [1], potentially has high-resolution range profile. LFM signal is a traditional radar waveform with many merits [2]. Its value of $B_w\tau(2v/c)$ is ordinarily much smaller than 1 when a target moves slowly, where B_w, τ, v and c are bandwidth, pulsewidth, radial velocity and light speed, respectively. An echo model without stretching is fit for this case [3]. However, Doppler dispersion due to large bandwidth of UWB signal will cause negative effects on velocity estimate. Many techniques have been discussed to estimate the target range and radial velocity for the pulse LFM wideband radar [4,5]. Although the maximum entropy (ME) technique [4] is computationally more intensive than the maximum likelihood estimator (MLE) [5], the performance of the latter degrades when a target comprises multiple comparable dominant scatterers.

Generally, two-dimensional fast Fourier transform (2-D FFT) is implemented in the fast and slow time plane to get the slant range and radial velocity of a motion target. Nevertheless, the target usually moves over multiple range cells during the time of energy accumulation, causing not only range profile distortion, but also poor velocity estimation. Since the Doppler frequency in a radar is equivalent to spatial frequency in a uniform linear array (ULA), velocity calculation of a radar and DOA estimation of a ULA are two isomorphic problems in concept. This problem is similar to the relationship between the pulsed-wave Doppler ultrasound applied to clinical diagnosis and DOA estimation [6]. There are many subspace based DOA estimation methods for wideband coherent signal, such as the coherent signal subspace method (CSSM) [7], the weighted average of signal subspaces (WAVES) [8], the test of orthogonality of projected subspaces (TOPS) [9], the extension of TOPS (ETOPS) [10], 2-DPDFT [11], and so on. The performances of CSSM and WAVES are sensitive to the preliminary DOA estimates required to generate focusing matrices. Although TOPS and its modified version ETOPS are proposed without any initial DOA estimations, the performance of TOPS is greatly dependent on the selection of reference frequency [10] and ETOPS is much heavier in computational burden than TOPS under the same conditions. However, 2-DPDFT

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does not require any initial DOA estimations and its performance is independent of reference frequency choice. In addition, it is especially suitable for real-time implementation.

In this paper, 2-DPDFT is utilized to estimate high-resolution radial velocities of slowly moving targets for pulse LFM UWB radars. Different radial velocities correspond to straight lines with different slopes after 2-D FFT. The discreteness nature of 2-D FFT causes these lines can hardly pass their corresponding discrete points directly. Thus, an interpolation procedure is necessary [12] before 2-DPDFT. In addition to the inherent advantages of 2-DPDFT [11], HREVRP not only effectively prevents the measured velocity from range profile distortion and range-Doppler coupling, but can yield high-resolution range profile by phase compensating with the velocity. A range of radial velocities also is derived according to the corresponding requirements.

The paper is arranged as follows. Section 2 briefly shows the pulse LFM UWB signal model and 2-D FFT method. In Section 3, we discuss how 2-DPDFT is applied to high-resolution velocity estimation for UWB radars and how the high-resolution range profile is achieved through phase compensation. The simulations are presented in Section 4. We conclude this paper in the last section.

2. Pulse LFM UWB signal model and 2-D FFT method

Assume that the received additive noise is Gaussian complex random process with zero mean, and the transmitted signal contains N LFM UWB pulses

$$S_T(t)=\sum_{n=0}^{N-1} e^{j\pi k(t-nT_p)^2} e^{j2\pi f_c t}, \quad 0\le t\le \tau \tag{1}$$

where k, T_p and f_c denote chirp rate, pulse repeat interval (PRI) and carrier frequency, respectively. The received signal [3] can be given by

$$S_R(t)=\sum_{n=0}^{N-1} e^{j\pi k(t-nT_p-\tau_d(t))^2} e^{j2\pi f_c(t-\tau_d(t))} \tag{2}$$

when a target moves at low velocity and the value of $B_w\tau(2v/c)$ is much smaller than 1, where $\tau_d(t)$ equaling $2(R_0+vt)/c$ denotes time delay and R_0 is the initial slant range between radar and target. The reference signal model used for pulse compression is approximately assumed to be (1). Hence, the result of pulse compression is

$$\begin{aligned} S_0(t)=S_R(t)S_T(t)^* &= \sum_{n=0}^{N-1} e^{j\pi k[\tau_d(t)^2-2(t-nT_p)\tau_d(t)]} e^{-j2\pi f_c \tau_d(t)} \\ &\triangleq \sum_{n=0}^{N-1} e^{j\phi(t)} \end{aligned} \tag{3}$$

where $(\cdot)^*$ denotes the conjugation of $(\cdot)$, $\phi(t)$ is the phase of $S_0(t)$ that can be expanded by

$$\begin{aligned} \phi(t) &= \arg(S_0(t)) \\ &= \pi k\left(\frac{2(R_0+vt)}{c}\right)^2 - 2\pi(kt-knT_p+f_c)\left(\frac{2(R_0+vt)}{c}\right) \\ &= 4\pi[k(v^2-vc)t^2+(2kR_0v-ckR_0+ckvnT_p-cf_cv)t \\ &\quad +R_0(kR_0+cknT_p-cf_c)]/c^2 \end{aligned} \tag{4}$$

where $\arg(\cdot)$ indicates the phase of $(\cdot)$. Assume that t is equal to nT_p+mT_s, and T_p equals MT_s, where T_s denotes a time sampling interval and M is the number of samples during T_p. Then, (4) can be discretely rewritten as

$$\begin{aligned} \phi(n,m) &= 4\pi\Big[k(v^2-vc)(nT_p+mT_s)^2 \\ &\quad +(2kR_0v-ckR_0-cf_cv+ckvT_pn) \\ &\quad \times(nT_p+mT_s)+R_0(kR_0-cf_c+ckT_pn)\Big]/c^2 \\ &= \frac{4\pi kv^2T_p^2}{c^2}n^2+\frac{4\pi v(2kR_0-cf_c)T_p}{c^2}n \\ &\quad +\frac{4\pi kv(2v-c)T_pT_s}{c^2}mn+\frac{4\pi kv(v-c)T_s^2}{c^2}m^2 \\ &\quad +\frac{4\pi(2kR_0v-ckR_0-cf_cv)T_s}{c^2}m+\frac{4\pi R_0(kR_0-cf_c)}{c^2} \\ &\triangleq c_1n^2+c_2n+c_3mn+c_4m^2+c_5m+c_0 \\ &\quad (n=0,1,\ldots,N-1; \quad m=0,1,\ldots,M-1) \end{aligned} \tag{5}$$

Eq. (5) is composed of six terms: the first is Doppler spread, the second contains Doppler, the third is range–Doppler coupling, the fourth is range spread, the fifth contains target range and the sixth is constant. The fifth term of (5) is executed via FFT to yield the range bin of the target:

$$\begin{aligned} l &= \frac{2(2kR_0v-ckR_0-cf_cv)MT_s}{c^2} \\ &= \underbrace{-\frac{2kR_0MT_s}{c}}_{\text{range}}+\underbrace{\left(-\frac{2f_cMT_sv}{c}+\frac{4kR_0MT_sv}{c^2}\right)}_{\text{range shift}} \end{aligned} \tag{6}$$

According to (6), the range profile of the target shifts along range dimension, so that it is difficult to accumulate energy in slow time dimension. Similarly, the corresponding velocity cell of the target measured via FFT of the second term of (5) can be mathematically expressed by

$$d=\frac{2v(2kR_0-cf_c)NT_p}{c^2}=\underbrace{-\frac{2f_cNT_pv}{c}}_{\text{velocity}}+\underbrace{\frac{4kR_0NT_pv}{c^2}}_{\text{velocity shift}} \tag{7}$$

We can see that the first term in the right hand side of (7) indicates the true radial velocity of the target. However, the velocity profile shifts with R_0 in terms of the second term of (7).

3. HREVRP algorithm and ambiguous velocity analysis

3.1. Analogy between pulse UWB velocity and DOA

The relationship between Doppler frequency f_d and temporal frequency f_t in a radar can be analytically shown by

$$f_d=\frac{2v}{c}f_t \tag{8}$$

The time delay in a ULA due to distance difference (i.e. $D'\sin\theta$) is

$$\tau_{DOA}=\frac{D'\sin\theta}{c} \tag{9}$$

where D' is the distance between two consecutive ULA elements, θ denotes the DOA of wavefront. This delay