

Localization of Vibrating Targets Using Dual-Frequency Synthetic Aperture Radar and Time-Frequency Analysis

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Abstract

An important task in urban sensing applications is to accurately localize moving and vibrating targets in the presence of significant background clutter. A dual-frequency radar, which estimates the range of a target based on the phase difference between two closely spaced frequencies, has been shown to be a cost-effective approach for range estimation of a moving target. Previous work has shown that the use of time-frequency analysis techniques provides an estimate of instantaneous Doppler signature and enhanced signal-to-noise ratio (SNR), thereby enabling the range estimation of multiple moving targets and significantly improving the estimation accuracy. In this paper, we consider the combined use of these technologies with a synthetic aperture array for the localization of inanimated moving targets. The synthetic array aperture provides the capability of high-resolution spatial localization of multiple moving targets, as well as determining the orientation of the vibration.

1. Introduction

Urban sensing supporting through-the-wall radar imaging (TWRI) is an emerging technology attractive to a variety of civilian and military applications [1-2]. This technology can also be used by firefighters to detect and locate survivors, by criminal justice officers for enhanced situational awareness and tailored tactical operations, and in search and rescue operations in natural disasters. In these applications, it is desirable to obtain not only the layout of the building, including types and locations of walls, but also localization of both moving and stationary targets within enclosed structures.

There are many challenges facing the development of a successful TWRI system to meet the urban sensing requirements. From the system perspective, a TWRI is required to be low cost, light weight, reliable, portable, and user-friendly. To meet such requirements, Doppler radars based on narrow-band signals are often preferred. In particular, a dual-frequency continuous-wave (CW) radar, which estimates the range of a target based on the phase difference between two closely spaced frequencies, has been shown to be a simple and cost-effective approach to provide range estimation of a moving target [3]. The use of time-frequency analysis techniques in conjunction with a dual-frequency CW radar provides an estimate of instantaneous Doppler signature and enhanced signal-to-noise ratio (SNR), and thus enables the range estimation for multiple targets and significantly improves the estimation accuracy [4].

On the other hand, accurate target localization of the targets is desired, preferably from a standoff distance. This requires an array with a large number of antenna elements and a large aperture. However, in most TWRI applications, it is difficult to afford such array configurations. As a result, a dual-frequency radar exploiting synthetic array aperture becomes a desirable system configuration.

The large number of virtual array elements and the corresponding synthetic array aperture allow us to achieve several advantages in addition to those resulting from the use of the dual-frequency CW radar exploiting time-frequency analysis. Such advantages include high-resolution target localization, separation of multiple targets, and operation from large stand-off distance.

2. Dual-Frequency Radar

We consider a simple scenario where there exists line-of-sight (LOS) between the antenna position and the target. When there is a wall obstruction between the radar positions and the target, the wall effects can be compensated, provided that the wall parameters (thickness, dielectric constant, and orientation) are known [5-6]. Estimation of uncertain wall parameters was also discussed in [5].

Consider a dual-frequency CW radar operating at frequencies f_1 and f_2 . The baseband radar return at frequency f_i , $i = 1, 2$, can be expressed as,

$$s_i(t) = \rho_i(t) \exp(-j\phi_i(t)), \quad i = 1, 2, \quad (1)$$

where $\rho_i(t)$ and $\phi_i(t)$ are, respectively, the range-dependent amplitude and the phase of the return corresponding to the i -th frequency of operation. If $R(t)$ is the law of motion of the target, then the Doppler frequency shift, $f_{D,i}(t)$, is the differential of the phase, $\phi_i(t) = 4\pi f_i R(t) / c$, given by

$$f_{D,i}(t) = -\frac{1}{2\pi} \frac{d\phi_i(t)}{dt} = -\frac{2f_i}{c} \frac{dR(t)}{dt}, \quad i = 1, 2. \quad (2)$$

If both phases are measured modulo 2π , then

$$\phi_1(t) = \frac{4\pi f_1 R(t)}{c} + 2n\pi, \quad \phi_2(t) = \frac{4\pi f_2 R(t)}{c} + 2m\pi, \quad (3)$$

where m and n are unknown integers. Accordingly [3]

$$R(t) = \frac{c}{4\pi(f_2 - f_1)} (\phi_2(t) - \phi_1(t)) - \frac{c(m - n)}{2(f_2 - f_1)}. \quad (4)$$

The second term in the above equation induces ambiguity in range. For the same phase difference, the range can assume infinite values separated by a maximum unambiguous range $R_{\max} = c / [2(f_2 - f_1)]$. In urban sensing applications, suffi-

cient unambiguous range can be achieved by properly selecting the frequency difference between the two carriers.

The advantages of using time-frequency representations for Doppler signature analysis are multi-fold. An example of time-frequency representations is the short-time Fourier transform (STFT), defined for signal $x(t)$ as

$$F_x(t, f) = \int_{-\infty}^{\infty} x(\tau)h(\tau - t)e^{-j2\pi f\tau} d\tau, \quad (5)$$

where $h(t)$ is the window function.

3. Synthetic Array Processing

Consider a simplified point target model, where the point target vibrates according to the following expression:

$$\begin{aligned} x(t) &= x_0 + D \cos(2\pi f_0 t + \phi) \cos(\theta), \\ y(t) &= y_0 + D \cos(2\pi f_0 t + \phi) \sin(\theta), \end{aligned} \quad (6)$$

where (x_0, y_0) is the coordinate of the vibration center, D is the maximum displacement, f_0 is the vibration frequency, ϕ is the initial phase, and θ represents the direction of vibration. In addition to x_0 and y_0 , other unknown vibrating target parameters include D, f_0 , and θ . ϕ is usually of no interest.

Let (x_m, y_m) be the coordinate of the m -th radar position. The received signal at the m -th radar position for carrier frequency f_i can be expressed as

$$s_{m,i}(t) = \frac{k}{r_m} \exp[j(2\pi f_i t - \frac{4\pi r_m}{\lambda_i})], \quad i=1, 2, m=1, \dots, M, \quad (7)$$

where k is a constant, λ_i is the wavelength, and $r_m = [(x_m - x(t))^2 + (y_m - y(t))^2]^{1/2}$ is the distance between the target center and the m -th radar position, which can be estimated at each radar position using the dual-frequency radar. Performing discrete Fourier transform over a long time period yields discrete spectra corresponding to multiples of the vibrating frequency f_0 . Thus, f_0 can be easily estimated. Then, estimating phase difference at the f_0 spectrum points eliminates the effect of position displacement due to vibration and yields a robust estimate of r_m .

The following least square fitting fuses the observations made at the M radar positions:

$$(\hat{x}_0, \hat{y}_0) = \arg \min_{(x,y)} \sum_{m=1}^M [(x_0 - x_m)^2 + (y_0 - y_m)^2 - \hat{r}_m^2]. \quad (8)$$

Furthermore, it can be shown that the Doppler frequency at the m -th radar position can be expressed as

$$f_{D,m}(t) = (4\pi f_0 D / \lambda) \sin(2\pi f_0 t) \sin(\beta_m - \theta), \quad (9)$$

where β_m is the angle between the direction-of-arrival (DOA) of the target and the y -axis, observed at the m -th radar position. Thus, the peak Doppler frequency is a function of β_i and θ can be found by interpolating the peak Doppler frequency with respect to the radar position such that $\theta = \pi/2 - \beta_{\max}$ where β_{\max} is the angle corresponding to the maximum peak Doppler frequency, and D can be obtained accordingly.

4. Simulation Results

Consider a fan with metallic blades, rotating at 5 cycles/sec (yielding 20 Hz equivalent frequency with 4 blades), and the

blade tip is 20 cm from the center. The carrier frequencies of the dual-frequency radar are 1 GHz and 1.005 GHz, respectively. The sampling frequency is 10 kHz, and data of 0.5 second duration is used for estimation. Fig. 1 shows the synthetic array geometry. The coordinate of the fan center is (0, 5) m, and 10 radar positions, uniformly located along the x -axis with $x_m = -3, \dots, 6$ m, are assumed. θ is set as 80° . The input SNR is 0 dB. Fig. 2 shows the spectra at two selected radar positions. Both spectra show clear 20 Hz fundamental vibration frequency. Fig. 3 shows STFT results at the same radar positions where the peak Doppler frequencies are different. Using the methods described in Section 3, the following results are obtained from 20 independent trials:

	x_0	y_0	D	f_0	θ
Mean	0.031m	4.983m	19.89cm	19.0068 Hz	80.17°
STD	0.171m	0.218m	0.16cm	0.0120 Hz	3.51°

The full paper submission will include simulation and experimental results for multiple vibrating targets. Real-data experiment will be conducted at Villanova University's Radar Imaging Lab where synthetic array aperture is achieved by moving a dual-frequency radar on a two-dimensional (2-D) positioner.

References

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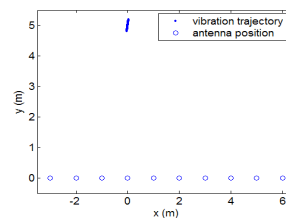


Fig. 1 Synthetic array geometry (left to right: 1st to 10th position)

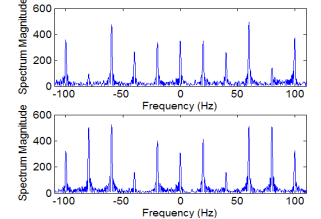


Fig. 2 Spectra at f_1 (top: 1st position, bottom: 9th position)

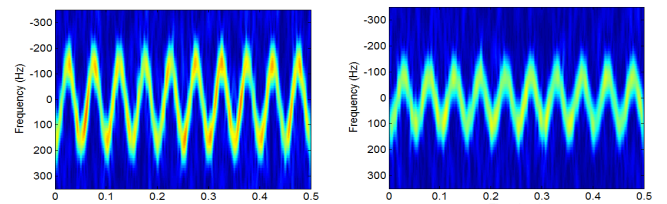


Fig. 3 STFT results at f_1 (left: 1st position; right: 9th position)