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Inverse synthetic aperture radar phase adjustment and cross-range scaling based on sparsity

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A B S T R A C T

Due to inherent sparsity of ISAR images, compressive sensing theory has been used to obtain a high resolution image. However, before applying sparse recovery methods, the phase error due to the translational motion of target is compensated by autofocusing algorithms and the target rotation rate is estimated by cross-range scaling methods. In this paper, a comprehensive matrix model for a uniformly rotating target that includes the phase error and chirp-rate of the target is derived. Then by using sparsity and minimum entropy criterion, the estimation of residual phase error and the rotation rate is refined. In order to reduce the computational load, we simplify the model and by an iterative method based on adaptive dictionary, the phase error and chirp-rate are estimated separately. Actually, by exploiting a two-dimensional (2D) optimization method and the Nelder–Mead algorithm the phase adjustment is performed and the chirp-rate is estimated by solving a 1D optimization method for dominant range cells of the target. Finally, both simulation and practical data have been used to verify the validity of the proposed approach.

1. Introduction

Inverse synthetic aperture radar (ISAR) is a powerful signal processing tool for imaging moving targets usually on the two dimensional (2D) down-range cross-range plane [1]. ISAR imagery plays an important role especially in military applications such as target identification, recognition, and classification [1,2]. In order to achieve a high resolution ISAR image, the radar transmits large bandwidth signal and integrates the received echoes of a moving target from different aspect angles coherently.

Recent results in signal processing have demonstrated the ability of Compressive Sensing (CS) to reconstruct a sparse or compressible signal from a limited number of measurements with a high probability by solving an optimization problem [3,4]. Recently, CS has been adopted to obtain high-resolution ISAR images [5–11]. In [7–11] the authors assume that range alignment and phase adjustment have been completely done by conventional methods such as [12–14] and then a sparsity-driven algorithm is used to generate high-resolution ISAR images. Specifically, in [11], a high-resolution fully polarimetric ISAR imaging is proposed that images are constructed by means of the sparse recovery algorithm under the constraint of the joint sparsity. Actually, a 2D smoothed l0 norm (2D-SL0) reconstruction algorithm introduced in [15] is exploited by [11] to solve the sparsity-driven optimization problem. However, sparsity can be used to refine the phase adjustment, for example in [16] sparsity is exploited for joint SAR imaging and phase error correction. In [17] and[18] Bayesian compressive sensing (BCS) are developed for both ISAR imaging and phase adjustment for full aperture and sparse aperture (SA) conditions, respectively. Moreover, in [19] by utilizing sparse Bayesian learning, an autofocus technique is proposed to obtain a focused high-resolution radar image. On the other hand, in the above mentioned sparse based ISAR imaging the rotation rate is not estimated and therefore the obtained image cannot be scaled in the cross-range dimension. In [10] and [20] sparsity is applied to estimate the unknown rotation rate. Specifically, in [10] a parametric sparse representation method is exploited for both ISAR imaging and cross-range scaling of rotating targets.

In this paper, a comprehensive matrix model for a uniformly rotating target that includes both the phase error and chirp-rate of the target is derived. In order to simplify the sparse problem, the phase error and chirp-rate are estimated separately. Before solving the sparsity-driven algorithm the coarse motion compensation is performed by conventional methods introduced in [21–23], then

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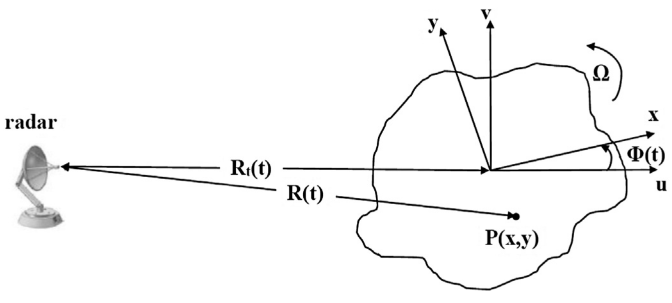

Fig. 1. Geometry of a rotating target in ISAR model.

by using joint constraint of sparsity and minimum entropy, the estimation of residual phase error is refined through an iterative method based on adaptive dictionary. Moreover, to speed up the reconstruction and reduce the memory usage, we exploit the dictionary so that the 2D-SL0 reconstruction algorithm can be used. In other words, by exploiting a two-dimensional (2D) optimization method and the Nelder–Mead algorithm [24] both phase adjustment and ISAR imaging are evaluated.

After fine motion compensation, the chirp-rate is estimated. In [25], the author proposed an algorithm for cross-range scaling. Therefore, we first estimate an initial value for chirp-rate using the method of [25], and then by an iterative approach, solve a 1D optimization method for dominant range cells of the target and search the best chirp rate around the initial value.

The remainder of this paper is organized as follows. Section 2 introduces the signal model. In section 3 the proposed sparse based algorithm is introduced. Sections 4 and 5 present some simulation and experimental results to validate the algorithm, respectively. Finally, Section 6 concludes this paper.

2. Signal model

In this section, we first describe the geometry of the target and the signal model and then simplify this model. The geometry of the uniformly rotating target is shown in Fig. 1. When the target is in the far field of the radar, the instantaneous distance from the scattering center $P(x, y)$ to the radar can be approximated as

$$R(t) \cong R_t(t) + x\cos(\Omega t) - y\sin(\Omega t) \tag{1}$$

where $R_t(t)$ is the target's translation range distance from the radar and Ω is the angular velocity of the target which is constant during the CPI. If the CPI and the angular velocity of the target are small enough we can approximate $R(t)$ by a two-order Taylor's polynomial approximation as:

$$R(t) \approx R_t(t) + x - y\Omega t - \frac{x}{2}\Omega^2 t^2 \tag{2}$$

without loss of generality assume that the radar transmits a linear frequency-modulated (LFM) signal as

$$s(\tau) = \text{rect}\left(\frac{\tau}{T_p}\right)\cdot\exp\left\{j2\pi\left(f_c\tau + \frac{\alpha}{2}\tau^2\right)\right\} \tag{3}$$

where τ denotes the fast time, T_p is the pulse duration, f_c is the carrier frequency, α is the chirp rate, and rect(·) stands for the unit rectangular function. After the demodulation to baseband, the complex envelope of the received signal from $P(x, y)$ can be written in terms of the fast time τ and slow time t as:

$$u(\tau,t) = \sigma\cdot\text{rect}\left(\frac{\tau - \frac{2R(t)}{c}}{T_p}\right)\cdot\text{rect}\left(\frac{t}{T_o}\right) \cdot\exp\left\{-j4\pi\frac{R(t)}{\lambda}\right\}\cdot\exp\left\{j\pi\alpha\left(\tau - \frac{2R(t)}{c}\right)^2\right\} \tag{4}$$

where λ is the wavelength, c is the speed of light, T_o is the observation time and σ is the scatterer radar cross section (RCS) coefficient. According to the assumption of short CPI, the scattering characteristic is assumed to be stationary during the observing time. Due to the rotational motion of the target, at different dwell times t, the signal has different time delays in the fast time τ, which may cause migration through resolution cell (MTRC). In [26] and [27] some approaches have been presented to compensate MTRC efficiently. Assume that range alignment [12–14] and MTRC have been done, then by substituting (1) and (2) into (4) we will have

$$\begin{aligned} u(\tau,t) = \sigma\cdot\text{rect}\left(\frac{\tau - \frac{2(R_0+x)}{c}}{T_p}\right)\cdot\text{rect}\left(\frac{t}{T_o}\right)\exp\{j\phi_e(t)\} \\ \cdot\exp\left\{-j4\pi\frac{(R_0+x)}{\lambda}\right\}\cdot\exp\left\{j4\pi\frac{(y\Omega t)}{\lambda}\right\} \\ \cdot\exp\left\{j2\pi\frac{(x\Omega^2t^2)}{\lambda}\right\} \\ \cdot\exp\left\{j\pi\alpha\left(\tau - \frac{2(R_0+x)}{c}\right)^2\right\} \end{aligned} \tag{5}$$

where $\phi_e(t)$ is the phase error induced by translational motion of the target. In order to obtain the signal in range-frequency, slow-time domain we should first obtain Fourier transform of the LFM signal in (3), but the exact derivation is not straightforward, then a convenient approximate expression can be obtained by the Principle of Stationary Phase (POSP)[28] and the spectrum of the LFM signal becomes

$$S(f_\tau) = \text{rect}\left(\frac{f_\tau}{\alpha T_p}\right)\cdot\exp\left\{-j\pi\frac{f_\tau^2}{\alpha}\right\} \tag{6}$$

where f_τ is the range-frequency. Assume that the target of interest contains K scattering centers, then by using (6) the signal in the range-frequency slow-time domain is

$$\begin{aligned} u(f_\tau,t) = \exp\left\{\frac{-j4\pi(f_c+f_\tau)R_0}{c}\right\}\cdot\exp\{j\phi_e(t)\}\cdot\sum_{k=1}^{K}\sigma_k \\ \cdot\text{rect}\left(\frac{f_\tau}{\alpha T_p}\right)\cdot\text{rect}\left(\frac{t}{T_o}\right)\cdot\exp\left\{-j\pi\frac{f_\tau^2}{\alpha}\right\} \\ \cdot\left\{\frac{-j4\pi(f_c+f_\tau)x_k}{c}\right\}\cdot\exp\left\{\frac{j2\pi f_c x_k\Omega^2t^2}{c}\right\} \\ \cdot\exp\left\{\frac{j4\pi f_c y_k\Omega t}{c}\right\} \end{aligned} \tag{7}$$

Assume that the range frequency, f_τ, can be written as $f_\tau = f_n = (n-1)\Delta f, n = 1, 2, \ldots, N$, where Δf is the space between two samples in the frequency domain, and the corresponding aspect angle of a target with respect to the radar in the mth pulse is $\theta_m = -\Omega t_m = (m-1)\Omega T_{PRI}, m = 1, 2, \ldots, M$, where T_{PRI} denotes the pulse repetition interval. Therefore, (7) can be rewritten as

$$\begin{aligned} u_{m,n} = \exp\left\{\frac{-j4\pi(f_c+f_\tau)R_0}{c}\right\}\cdot\exp\{j\phi_e(t)\} \\ \cdot\sum_{k=1}^{K}\sigma_k\cdot\exp\left\{-j\pi\frac{f_n^2}{\alpha}\right\}\cdot\exp\left\{\frac{-j4\pi(f_c+f_n)x_k}{c}\right\} \\ \cdot\exp\left\{\frac{j2\pi f_c x_k\Omega^2t_m^2}{c}\right\}\cdot\exp\left\{\frac{-j4\pi f_c y_k\Omega t_m}{c}\right\} \end{aligned} \tag{8}$$