A Joint Technology of UAV SAR Based on OFDM Waveform

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Abstract. This paper presented a method based on compressed sensing that can be used for a joint technology of unpiloted aerial vehicles (UAV) radar detection and with the orthogonal frequency division multiplexing (OFDM) signal. OFDM is promising waveform in the next-generation future radar, it also brings the possibility of radar detection and wireless communication time-sharing processing under compatibility mode. An imaging method was performed by synthetic aperture radar imaging (SAR) with OFDM signals on the UAVs platform in this paper. Due to burden on data storage and transmission, an effective imaging algorithm is proposed to achieve high resolution with less collection data by UAV SAR based on compressive sensing focusing method. At the same time. The experimental data and simulation testified the proposed method.

Keywords: OFDM · UAV SAR · Radar-communication integration · Radar imaging

1 Introduction

In recent years, UAVs plays an important role in typical environment monitoring, target acquisition and information transmission [1]. Some researchers have studied the joint-design methodology of multicarrier detection technique and orthogonal frequency division multiplexing (OFDM) communication technique [2]. Kenneth Vines and his team also provide a C-Band UAV SAR based on integrated radar and communication design [3]. Several experiments have been taken to verify the usage of UAV SAR in typical working mode and GMTI based on radar- communication integration [4].

According to the characteristics and requirements of the UAVs, it can reduce the volume, power consumption and cost of the system through the joint design of radar detection and communication based on OFDM signal. The orthogonal frequency division multiplexing (OFDM) has become a crucial technique for the new generation at home and abroad [5]. OFDM radar signal processing was first proposed by Jankiraman in 1998, and recently researched in radar applications, such as target detection [6], high-resolution and wide-swath imaging [7]. Furthermore, UWB OFDM radar and GPS combination system is designed by Garmatyuk D, his team also used it as SAR imaging signal and proposed imaging algorithm which an improvement can be effected by use of the least squares estimate part [8, 9].

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Meanwhile, limited by shannon Nyquist sampling theorem, high resolution and large scene ground observation bring rigorous challenges to A/D sampling, data storage and transmission systems. However, the development of compressed sensing technology has brought great possibilities for solving this problem. A compressed sensing imaging method is presented based on wavelet sparse representation of scatter coefficients for strip map mode SAR [10]. As long as the signal satisfies the precondition of sparse in a specific transformation domain, the signal can be reconstructed without distortion with a high probability using a small amount of observed data. Some researchers have explored the problem of SAR [11, 12]. However, few studies have been on OFDM SAR with compressed sensing.

The primary focus of this paper is on radar imaging technology based on UAV OFDM SAR. The radar detection performance of OFDM signal is obtained by analyzing the ambiguity function. The imaging results of target can be obtained by two-dimensional matching filter. Meanwhile, high resolution large scene SAR imaging imposes a heavy burden on data storage and transmission systems. To alleviate this problem, a compressive sensing imaging method is proposed based on OFDM SAR.

2 Theory Basis

2.1 The Construction of Scenario Model

UAVs could implement orthogonal frequency multiplexing (OFDM) communications and radar detection joint modules simultaneously. It means target detection is performed by the means of radar signal processing. The UAV platform continuously emits OFDM signals to main objects in the surrounding environment, such as vehicles and buildings during movement. When the OFDM signal is scattered by the target, the time delay and doppler frequency of the echo signal will change. Reconstruction of original image can be achieved by the use of echo information, as shown in Fig. 1.

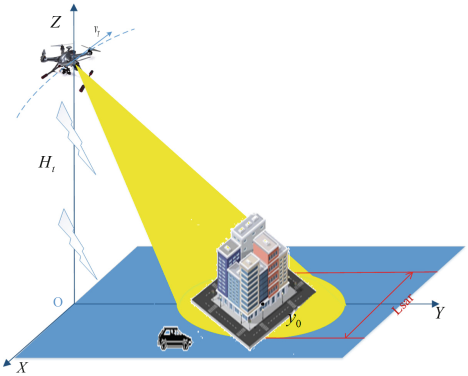

Fig. 1. OFDM UAV SAR model

2.2 The Ambiguity Function

As a means of radar waveform design and analysis, ambiguity function can describe the characteristics of the waveform and corresponding matched filter. When the optimal matching filter is adopted, it can be used to measure the resolution, measuring accuracy and ambiguity of the radar system. There are many ways to define the ambiguity function. This article adopts the definition as shown in Eq. 1.

$$\chi(\tau_d,f_d) = \int_{-\infty}^{+\infty} u(t)u^*(t+\tau_d)e^{j2\pi f_d t}dt \tag{1}$$

2.3 SAR Echo Model Based on OFDM Waveform

In the principle of orthogonal frequency division multiplexing (OFDM), an available signal bandwidth is divided into multiple sub band. It is assumed that the OFDM signal which the number of subcarriers is N can be represented by

$$u(t) = \frac{1}{N}\sum_{n=}^{N-1} d_n(t)\exp(j2\pi f_n t) \tag{2}$$

$$d_n(\mathrm{t}) = C_n(\mathrm{t})\exp(\mathrm{j}\,\varphi_\mathrm{n}(\mathrm{t})) \tag{3}$$

The diversity of communication waveform design is mainly reflected in the carrier modulation envelope $d_n(t)$. $C_n(t)$ represents the term of envelope amplitude, and $exp(\mathrm{j}\varphi_n(t))$ is the envelope phase term.

The imaging of SAR based on OFDM is considered into account of the establishment of the scene model. Assuming that the shared signal transmitting platform moves along the x-axis at a constant velocity v, the stationary point target P, the distance from the radar to the target is $R(t)$. Radar will transmit OFDM signal of N sub carrier in the state of motion, then the echo can be clearly expressed as

$$\begin{aligned} ss(t_f-\frac{2R(t_s)}{c},t_s) = \sigma w_r(t_f-\frac{2R(t_s)}{c})w_a(t_s)\frac{1}{\sqrt{N}} \\ \sum_{n=0}^{N-1} d_n(t_f-\frac{2R(t_s)}{c})\exp(\mathrm{j}2\pi f_n(t_f-\frac{2R(t_s)}{c})) \end{aligned} \tag{4}$$

Where σ is scattering coefficient, w_r presents time domain distance window function, time domain azimuth window function can be expressed as w_a, t_f is fast time series, t_s is defined as slow time sequence, R is regarded as the distance from radar to target, and c is the speed of light.

Assuming that the signal envelope, $d_n(f_r)$ is phase encoded, the reference signal of the corresponding matched filter can be represented as

$$u(t_f) = ss^*(-t_f) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\exp(-j\phi_m)\exp(-j2\pi f_n t_f) \tag{5}$$

After range matching filtering, the echo signal can be expressed as

$$\begin{aligned} s(t, t_m) &= F^{-1}\left\{F\left\{ss(t_f - \frac{2R(t_s)}{c}, t_s)\right\} * F\left\{u(t_f)\right\}\right\} \\ &= \sum_{n=1}^{N_0} B\sigma_n \sin c[\Delta f_r(t - \frac{2(R0 + x_n \sin\theta_0)}{c})] \\ &\cdot \exp(-j\frac{4\pi}{\lambda}R_0) \cdot w_a(t_m - x_n/v) \cdot \exp(j\pi\gamma_m(R_0)(t_m - x_n/v)^2) \end{aligned} \tag{6}$$

Assuming that $\rho_n = B\sigma_n \sin c[\Delta f_r(t - \frac{2(R_0 + x_n \sin\theta)}{c})] \cdot \exp(-j\frac{4\pi}{\lambda}R_0)$, the Eq. (6) can be regarded by

$$s(t, t_m) = \sum_{n=1}^{N_0} \rho_n w_a(t_m - x_n/v) \cdot \exp(j\pi\gamma_m(R_0)(t_m - x_n/v)^2) \tag{7}$$

2.4 The UAVs SAR Imaging Under-Sampled Measurement

High resolution and large scene ground observation bring a heavy burden on A/D sampling, data storage and transmission systems. This paper is designed to realize the recovery of under-sampled measurement echo data for UAVs OFDM SAR by the use of compressed sensing.

Compressed sensing is a method of recovering signals from linear observations by solving a highly nonlinear optimization problem. An N-dimensional real signal is consisted of a set of orthogonal bases $\{\varphi_i\}_{i=1}^{N}$

$$\rho = \Psi\theta \tag{8}$$

$\psi = [\varphi_1, \varphi_2, \cdots \varphi_N] \in R^{N\times N}$ is the dictionary matrix. This paper chooses the Fourier orthogonal basis, $\psi\psi^T = \psi^T\psi = I, \theta = [\theta_1, \theta_2, \cdots \theta_N]^T$. The compression of $\rho_{M\times 1}$ can be accomplished by an observation matrix Φ which is not related to an orthogonal basis dictionary matrix. And the radar echo signal is the following expression:

$$s_{M\times 1} = \Phi_{M\times N}\rho_{N\times 1} \tag{9}$$

Therefore, the observation matrix can be expressed as

$$\Phi = \left[s(t_m - (\frac{N}{2} - 1) \cdot \Delta\tau), \cdots s(t_m + \Delta\tau), \cdots s(t_m + (\frac{N}{2} - 1)\Delta\tau)\right]$$
$$s(t_m - i\Delta\tau) = \exp\left\{j\pi\gamma_m(R_0)(t_m - i\Delta\tau)^2\right\}$$

The data $s_{M\times 1}$ after range matching filtering is the under-sampled measurement echo data and $\rho_{N\times 1}$ is the data to be restored.

The purpose of compression sensing is to recover x from y. Convex optimization can be very simple to describe the situation, and the original signal will be solved as solving such a convex optimization problem.

$$\min\|y - T\theta\|_2 + \lambda\|\theta\|_1 \tag{10}$$

The recovery matrix. $T = \Phi\Psi^H$, $\rho_{N\times 1} = \Psi\theta$, is the reconstructed complex image of the range cell scene.

3 Simulation and Results

In this section, simulation results are used to validate the analysis previously. The OFDM signal is obtained by a series of random sequence with QPSK modulation, serial and conversion, IFFT transform. The carrier frequency of the signal is 38 GHz. The number of sub carriers is set as 512, the symbol cycle length is 16.67 us, the signal bandwidth is 100 MHz, and the number of symbols per carrier is set as 12. As the method shown above, the ambiguity function is shown in Fig. 2, which shows resolution performance intuitively.

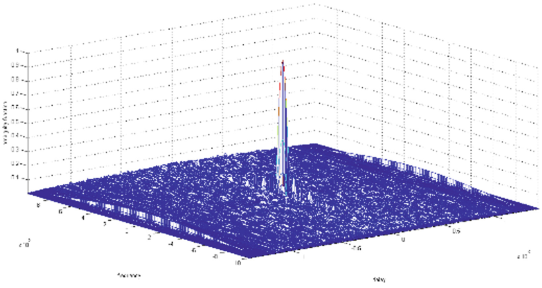

Fig. 2. The ambiguity function of OFDM signal

Theoretically, the range resolution only depends on the signal bandwidth $\Delta R = \frac{c}{2B} = 1.5\,\mathrm{m}$, the velocity resolution, which is related to the signal carrier frequency and the accumulated time length, is $\Delta v = \frac{1}{2}\lambda\Delta f = \frac{1}{2}\frac{c}{f_c}\frac{1}{T_{all}} = 23.68$ m/s. As is shown in Figs. 3 and 4, the equivalent bandwidth at the 4 dB point which corresponds to range resolution is $0.763 \times 2 = 1.526\,\mathrm{m}$ and the velocity resolution is $11.85 \times 2 = 23.7$ m/s The result of the simulation is consistent with the theoretical value.

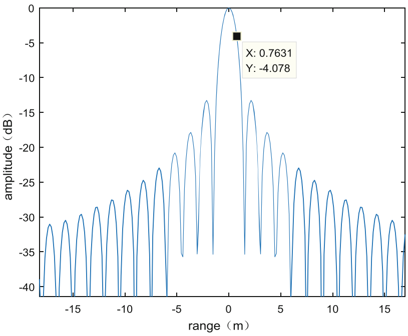

Fig. 3. Range profile simulation results

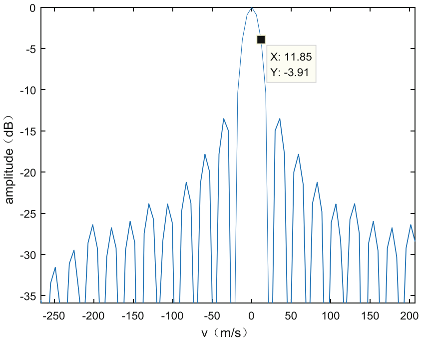

Fig. 4. Doppler frequency simulation results

The signal for radar detection and communication is transmitted simultaneously by UAVs. Considering the storage and transmission burden of large amount of data, the reconstruction of image is carried out by using down-sampling data. The processing of signal is shown in Fig. 5. The echo signal is convoluted with the reference signal in the fast time domain. The observation matrix is constructed in the slow time domain, which transforms the azimuth compression into solving the convex optimization problem. There are 5 point targets near the center of the scene at (Xc, 0), (Xc + 10 m, 0), (Xc − 10 m, 0), (Xc, 20 m), (Xc, −20 m) in the simulation. Assuming that echo data is down sampling at random, the echo received by radar is 0.8 times that of the original data. Figure 6 shows the echo data of the descending sampling. The results of range matching filtering with the loss of signal are presented in Fig. 7.

Results are shown in Fig. 8, where it could be seen that the target distance position can be obtained after correlation processing. As shown in Fig. 9, there are five targets in the scene which could be obtained by the means of compressed sensing. Compressive sensing parameters are set as discussed in Sect. 2.5 where η is equal to 2.

Compressed sensing is of great significance for the recovery of missing data in radar imaging. The influence of compressive sensing on SAR imaging performance is mainly reflected in the result of azimuth data compression. The use of compressed sensing has certain limitation on the amount of missing data. In the absence of random 0.3 times the original data of the information, it could still get accurate the position information. If the sampling rate continues to be lowered, the signal cannot be recovered well and the azimuth will appear blurred. The position of the target cannot be obtained accurately because of the elevation of side lobe in Table 1. It can be described that the trend of peak side lobe rate (FSLR) with the percentage of echo data is shown in Fig. 11 (Fig. 10).

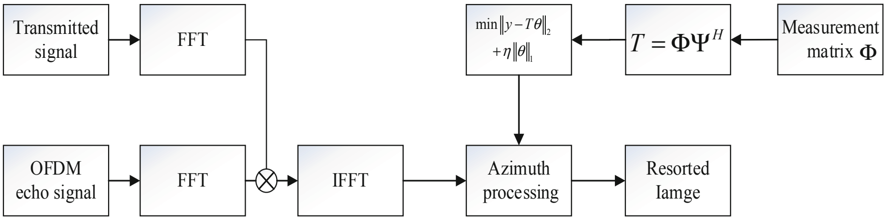

Fig. 5. The flow chart for signal processing

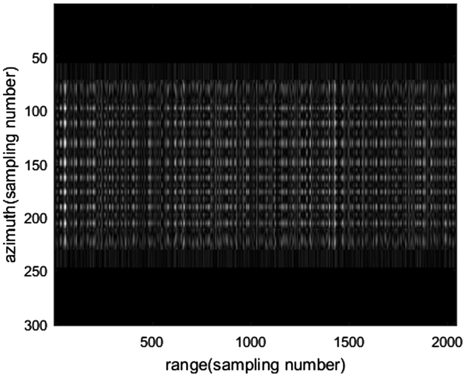

Fig. 6. The echo data of the descending sampling results

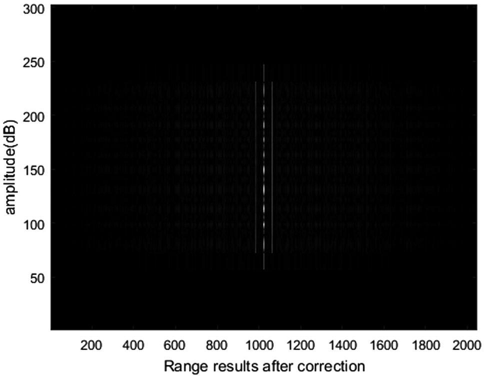

Fig. 7. Range compression simulation results

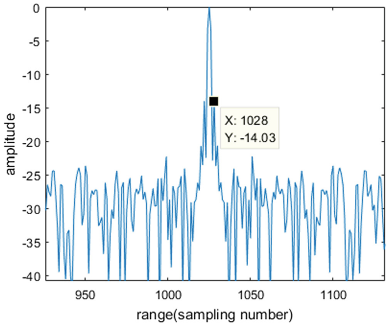

Fig. 8. Range profile results

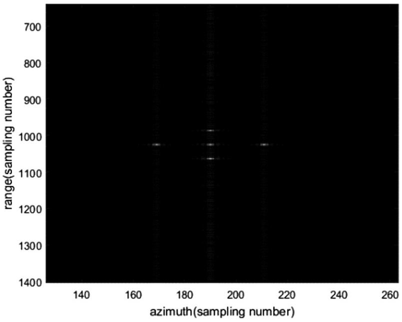

Fig. 9. OFDM SAR simulation results based on CS

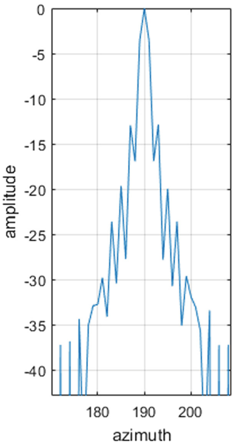

Fig. 10. 80% down sampling results.

Table 1. The relationship between echo data percentage and FSLR

Echo data percentage	FSLR
100%	−34.9 dB
90%	−34.7 dB
70%	−27.3 dB
40%	−22.83 dB
20%	−19.34 dB
1%	−8.17 dB

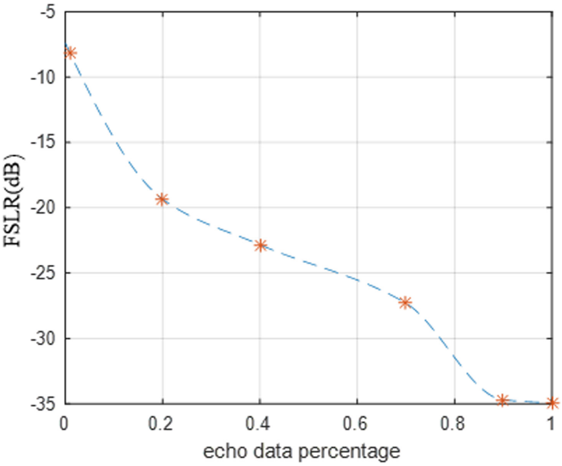

Fig. 11. The FSLR with echo data percentage

4 Conclusion

A joint technology of unpiloted aerial vehicles (UAV) radar imaging system based on OFDM signal is established to get the high-resolution imaging of the target, and it is applied to the actual situation. By using sparse reconstruction algorithms and the imaging processing the imaging of target was successfully focused by less raw data, which is suit for UAV radar with the waveform of the orthogonal frequency multiplexing (OFDM). The experimental data and simulation testified the proposed method. This research will enhance the understanding of radar-communication integration with small unpiloted aerial vehicles.

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