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An improved radar detection and tracking method for small UAV under clutter environment

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Dear editor,

The unmanned aerial vehicle (UAV) is a popular aerial instrument in both military and civil fields [1]. Radar is an efficient tool for aerial target surveillance and target parameter estimation [2] and has been widely used for air control. However, in recent years, it has become a challenge for radar to monitor this kind of small and low-altitude flying target [3]. Therefore, it is necessary to investigate the detection and tracking techniques of UAVs.

For UAV detection and tracking, the key problem is clutter suppression. Because a UAV is easily influenced by ground clutter, false alarms and missed detections often occur. Moreover, the trajectory of a UAV is easily interrupted. The conventional clutter suppression methods include moving target indication (MTI) and moving target detection (MTD) which can suppress only the mainlobe of the clutter and do not offer good performance for small targets. In contrast, the CLEAN algorithm can suppress the sidelobe of clutter but suffers from a large computation burden [4]. The time-frequency analysis methods, such as wavelet transform, short-time Fourier transform (STFT) [5], and empirical mode decomposition (EMD) [6], have also been introduced to separate the effective target from the clutter. However, detection and tracking of small UAVs under cluttered environments remain as challenges.

In this study, an improved radar detection and tracking method for small UAVs is proposed. Based on the conventional detection and tracking process, the additional EMD-based detection is introduced. In EMD-based detection, the possible range of cells and speed obtained by the target's tracking information is utilized to predict the possible range of cells of a UAV, and the target detection is performed only in this predicted range of cells. Meanwhile, the EMD is also used to separate the effective Doppler signal of the target from the received signal. In addition, the false targets are removed based on the speed inconsistency with the existing trajectories of targets.

Target detection based on EMD. In this study, EMD is used to separate the effective Doppler signal of a target from the received signal. However, multiple components (intrinsic mode function, IMF) will be obtained after EMD decomposition, in which some of the components may contain the target's signal, so effective EMD components must be selected first.

For EMD components that contain a target signal, its Doppler spectrum has a peak on one side, which will affect the similarity of two sides of the spectrum. Here, the spectral centroid and cross correlation coefficient are used to extract effective EMD components.

First, the difference between the spectral centroids on both sides of the spectrum is calculated,

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where the spectral centroid can be estimated by the centroid method as

$$\hat{f} = \frac{\sum_{f=0}^{f'} f \times F(f)}{\sum_{f=0}^{f'} F(f)}, \quad (1)$$

where f is the frequency in the Doppler domain, and $F(f)$ is the power spectral density.

If the difference between two spectral centroids is greater than a set threshold, this EMD component will be selected for subsequent target detection. Otherwise, the cross-correlation coefficient of two sides of the spectrum is further used to make a final decision on whether this EMD component will be selected. The cross-correlation coefficient can be calculated as

$$\rho = \frac{\mathrm{Cov}(S_l, S_r)}{\sqrt{D(S_l)} \times \sqrt{D(S_r)}}, \quad (2)$$

where S_l and S_r are two sides of the spectrum, $\mathrm{Cov}(\cdot)$ represents the variance function, and $D(\cdot)$ represents the covariance function. If ρ is less than a set threshold, this EMD component will also be selected.

After effective EMD component selection, constant false alarm detection (CA-CFAR) is performed for target detection. Note that because the target signal may exist in different components, one target may be detected repeatedly, and only one will remain for detected targets with the same Doppler frequency. What is more, only a detected target whose speed is similar to the trajectory speed finally remain. The next section will present how to introduce the proposed EMD-based detection method into conventional detection and tracking processing.

Improved detection and tracking processing for small UAV. For improved detection and tracking processing, there are basically two processing flows: one is for new trajectory formation using conventional detection processing, and the other is for weak target detection in a cluttered environment by using the proposed EMD-based detection processing. The specific diagram of detection and tracking for a small UAV is shown in Figure 1(a). In conventional detection and tracking processing, pulse Doppler and two-dimensional CA-CFAR detection are adopted with a low false alarm rate for clutter suppression. The nearest neighbor method and Kalman filtering are used to build the new trajectory. Based the existing trajectory information, the proposed EMD-based detection is used to ensure continuous and stable tracking of weak targets. If targets are detected by both conventional detection and EMD-based detection, the detection result will be fused as one target. The subsequent tracking processing still uses the nearest neighbor method and Kalman filtering.

Performance analysis. The performance of the proposed method under different signal-to-clutter ratios (SCRs) is analyzed through simulation. A complex signal that contains a target with a velocity of 15 m/s and clutter with a spectrum width of 40 Hz and a spectrum center of 0 is simulated. The clutter is simulated by the spherically invariant random process. SCR is calculated by the ratio of the average power of the target signal and the average power of clutter, and it ranges from -40 dB to 0 in this simulation. Monte Carlo simulation is used and the detection rate versus SCR of our proposed method and conventional two-dimensional CFAR are given in Figure 1(b). It can be seen that the proposed method has better performance when the SCR is lower.

Experimental validation. The experimental data are collected by a Ku-band phased array radar with a signal band of 80 MHz and a pulse repetition frequency of 8.3 kHz. In the experiment, the flight height of the small UAV (DJI Phantom 3 SE) is approximately 60 m with a radial velocity of approximately 15 m/s. The UAV target is approximately 2 km from radar. Thus, the radar elevation is approximately 2°, and the received echo signal of the UAV is influenced severely by ground clutter. Using conventional two-dimensional detection and tracking, it can be found that missed detection exists, which could induce the interruption of the trajectory.

The detection and tracking result using the proposed method is shown in Figure 1(c). It can be seen that the detection rate of the UAV target is greater than that using the conventional method as marked by the red blocks. The missed detection rate of EMD-based detection is lower, and a more continuous trajectory could be obtained. This means that the proposed method has better performance for small target detection in a cluttered environment. Moreover, one of the EMD-based detection results ($t = 5.6135$ s) is introduced in detail. Two effective EMD components are selected based on the proposed spectrum centroid and cross-correlation coefficient method, in whice the threshold of the spectral centroid difference is 70 and the threshold of the cross correlation coefficient is 0.5, which are obtained by the variable-controlling method and the Monte Carlo simulation. After applying CA-CFAR in these two components, the UAV could be detected, with a radial velocity of 15.25 m/s. Thus, the experimental result shows the effectiveness and feasibility of the proposed method.

Conclusion. In this study, an EMD-based detec-

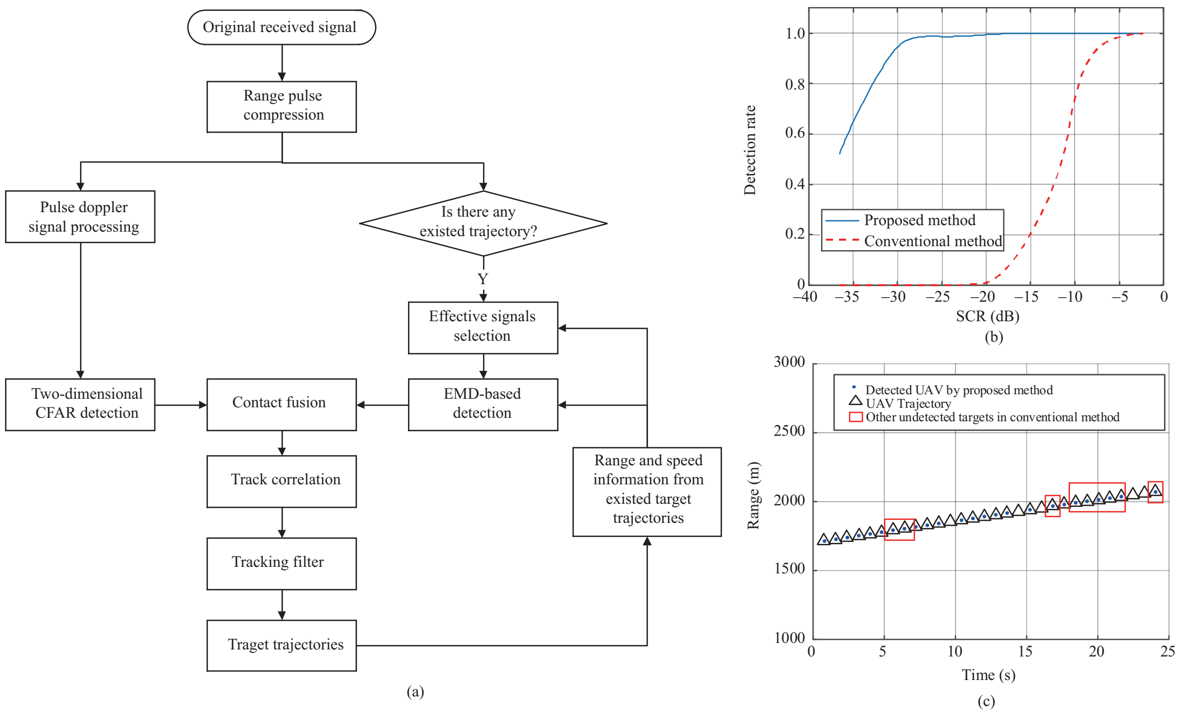

Figure 1 (Color online) (a) The diagram of the proposed detection and tracking processing; (b) the performance of two methods; (c) the UAV trajectory obatined by the proposed processing.

tion and tracking method is proposed for a small target in a cluttered environment. EMD is used to reduce the influence of clutters on small target detection. Based on the proposed EMD detection, an improved tracking processing method is then proposed, in which the target's trajectory information is also utilized to predict the possible range of cells and the possible flight velocity of the target for further false alarm suppression. Finally, the experimental results show that the proposed method has better anti clutter performance, and a more continuous trajectory of a small UAV could be obtained successfully with a lower missed detection rate.

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