# A Mini Radar System for Low Altitude Targets Detection

Kangkang Wu, Kaizhi Wang, Zhijun Yuan

***Abstract*—**This paper deals with a mini radar system aimed at detecting small targets at the low latitude. The radar operates at Ku-band in the frequency modulated continuous wave (FMCW) mode with two receiving channels. The radar system has the characteristics of compactness, mobility, and low power consumption. This paper focuses on the implementation of the radar system, and the Block least mean square (Block LMS) algorithm is applied to minimize the fortuitous distortion. It is validated from a series of experiments that the track of the unmanned aerial vehicle (UAV) can be easily distinguished with the radar system.

***Keywords*—**Unmanned aerial vehicle, interference, block least mean square, frequency modulated continuous wave.

## I. Introduction

A UAV is a low-cost and purchasable aircraft which has been widely used to execute missions of observation or detection. Due to the large number of the UAVs, especially the consumer-grade UAVs, the misuse of them will threat the security of the surrounding civil infrastructures and even lead to the widespread panic or economic disruptions. Furthermore, with the continuous improvement of the relevant laws, the demand for monitoring the illegal flight of the consumer-grade UAVs is growing rapidly. To meet the demand, there are many techniques that have been proposed to detect and track the illegal flight of UAVs, including acoustic sensing [1], Radio Emission Sensing [2], and radar. And the key problem is how to detect and extract the track of UAVs from the noise in the complex urban circumstance. In this paper, a mini radar system is introduced to monitoring small civil UAVs from a long distance with the block-LMS algorithm.

The characteristics of consumer-grade UAVs are low altitude and speed which are constrained by their basic mechanism. Moreover, the radar cross section (RCS) of this type aircrafts are too small as their carbon fiber blades approximate to a perfect electrical conductor and plastic material's dielectric properties are close to air, resulting in little reflection back to the receiver [3]. In response to these characteristics, some criteria are proposed to implement the mini radar system. The radar system works at the Ku-band and transmits the continuous wave to receive the backscattered signal from the UAV. For the smaller RCS, a wide bandwidth signal is adopted to highlight the UAVs and to improve the range resolution as well. In addition, there are two receiving antennas to accomplish the clutter cancellation or measure the height and velocity of the targets. Owing to the merits of the FMCW, the mini radar system has the advantages of light weight, small volume, and low energy consumption. The exterior of radar system is shown in Fig. 1.

Fig. 1 The exterior of the radar system

Since the radar may cope with the harsh conditions, a real-time and low complexity filtering algorithm is needed to suppress the additional noise in the backscattered signals. The Block LMS algorithm is an adaptive algorithm which updates its parameters without any prior knowledge about the input signals [4]. Compared with the LMS algorithm, the Block LMS algorithm requires less computation and has better performance [5]. Therefore, the Block LMS algorithm is applied to reduce the noise reduction in the radar system.

The paper is organized as follows. Section II introduces the basic configuration of the radar system. The derivation process of the Block LMS algorithm is described in Section III. Along with the introduced radar system, the experimental results are given in Section IV. Finally, conclusion is drawn at Section V.

## II. Composition of Radar System

Fig. 2 illustrates the structure of mini Radar system. The system consists of application terminal, auxiliary component, the radar front end, and the digital signal processing component.

The application terminal is used for communication between the radar front end and the host computer and displays the detection result. The auxiliary component consists of the compass module and the rotation platform. The azimuth angle can be yielded by the compass module, the pitch angle of UAV can be yield by interferometric processing of the signals from two receiving channels. And the rotation platform enables the system to investigate the surrounding situation. Moreover, Direct Digital Synthesizer (DDS) embedded in the radar front end generates the sawtooth FMCW. The digital signal processing component manipulates the collected

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samples and separates the targets from the background. The detail parameters of the radar system are listed in Table I.

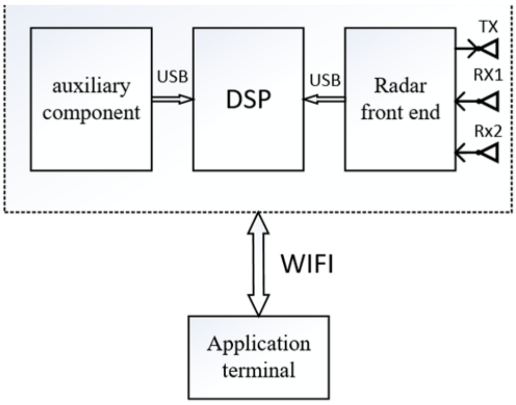


Fig. 2 Simplified radar diagram

TABLE I
SYSTEM PARAMETERS

| Systemic parameters | value |
|---|---|
| Center frequency | 15 GHz |
| Bandwidth | 1 GHz |
| Pulse width | 4 ms |
| Sampling rate | 20 MHz |
| Pulse repeat frequency | 200 Hz |
| Range resolution | 0.15 m |
| Coherent accumulation | 5 |
| Azimuth beam-width | 32° |
| Antenna gain | 20 dB |
| Polarization | HH |
| Transmitted power | 1 W |

Fig. 3 shows the time-frequency relationship of transmitted and the backscattered sig. A two-channel analog digital converter (ADC) is adopted to sample the backscattered data at a speed of 20 MHz. The resolution of the radar in range is

$$R_{res} = \frac{c}{2B} = 0.15m \quad (1)$$

where c equals the velocity of light and B is the bandwidth of transmitted signals. The phase of transmitted signals, without loss of generality, can be expressed as:

$$\varphi_t(t) = 2\pi\left(f_0 t + \frac{B}{2T}t^2\right) - \varphi_0 \quad (2)$$

where $\varphi_0$ denotes the initial phase and t ranges from 0 to T. Owing to the reflection, the delay between the transmitted and received signals equals $\tau = \frac{R+vt}{c}$, and the phase related to the delay is approximated to

$$\Delta\varphi(t) \approx \frac{2\pi f_0 R}{c} + \frac{2\pi(f_0 v+BR)}{Tc}t \quad (3)$$

Simultaneously, the beat frequency generated by reference signal and received signal approaches to

$$f_{BF}=\frac{BR+f_0 v}{Tc} \quad (4)$$

Assume that the movement of UAVs satisfies the requirements of stationary and low speed, and the magnitude of beat frequency is principally determined by the distance between the receiver and the targets. As the obtained signals have been contaminated by those noises generated in each processing step, using ensemble averaging can acquire the impact of noise cancellation at the expense of time consumed to average those adjacent pulses [6].

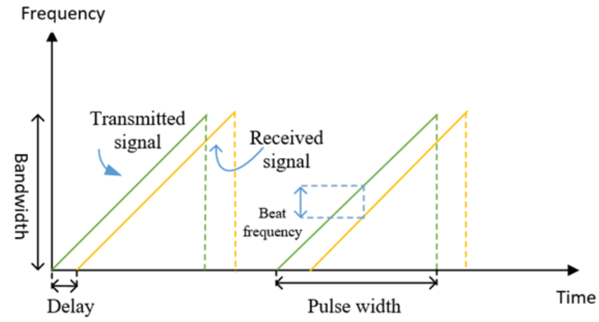


Fig. 3 FMCW waveform diagram

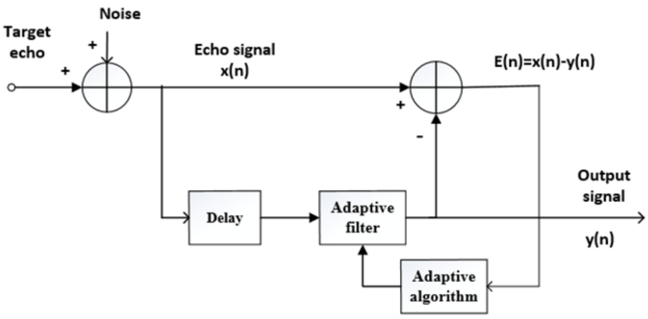


Fig. 4 Diagram of the Block LMS filter

## III. ADAPTIVE DATA PROCESSING

Due to the complex electromagnetic environment and terrain of the city, the backscattered signal is mixed with a large amount of clutter during transmission. To enhance the detection ability of the radar, adaptive algorithm is adopted in the system to overcome the small RCS of UAVs. Compared to traditional fixed parameter digital filters, adaptive algorithms manipulate input signals without obtaining their prior probability distribution, which indicates high flexibility and robustness. This type of algorithms is applied to extract the narrow-band signals from contaminated input signals through fleshing the value of tap weights and include some variants, such as LMS, RLS, and Block LMS. LMS is used widely for the reason of its simplicity and robustness, while its rate of convergence suffers the impact of original signals. Oppositely, RLS overcomes the drawback above-mentioned, but as the order of filter increases, the expense of computation augments simultaneously. As a trade-off between computational complexity and convergence, block LMS algorithm can be adopted to process the experiment results.

Fig. 4 shows the block diagram of block LMS algorithm.

The observed signal x is captured by AD and is a stationary stochastic sequence. To facilitate the analysis, the observed signal can be decomposed as $\mathbf{x} = \mathbf{s} + \mathbf{n}$ where s denotes a stationary stochastic signal, and **n** represents an additive zeros-mean random noise introduced in the entire process. To satisfy the requirement of steady-state, s can be considered as a deterministic signal merely related to the position of targets rather than the time. It is s that we manipulate to reconstruct the echo x via adaptive algorithm. Assume that $\mathbf{w}(\boldsymbol{k})$ is a $N \times 1$ vector and denotes the weight of filter-tap in the k-th block. In the $n^{th}$ step, the reference signal $\mathbf{u}(n)$ generated by the delay of observed signal can be written as

$$\mathbf{u}(\mathrm{n}) = [\mathrm{u}(n), \mathrm{u}(n-1), \cdots, \mathrm{u}(n-N+1)]^T \quad (5)$$

where superscript T denotes transpose. Thus, the outcome of the filter in $n^{th}$ step can be given by

$$\mathrm{y}(n) = \mathrm{w}^{\mathrm{H}}(\mathrm{k})\mathrm{u}(\mathrm{n}) \quad (6)$$

where H denotes Hermitian transposition. Therefore, the error, defined as the difference between the observed signal and the signal produced by filtering, can be calculated recursively as

$$\mathbf{e}(\boldsymbol{n}) = \boldsymbol{x}(\boldsymbol{n}) - \boldsymbol{y}(\boldsymbol{n}) \quad (7)$$

This equation is equivalent to the expression of the LMS algorithm. To minimize the error, a loss function can be defined as

$$\mathrm{J} = \frac{1}{2}\mathrm{E}\{(\mathrm{x}-\mathrm{y})^{\mathrm{T}}(\mathrm{x}-\mathrm{y})\} \quad (8)$$

Equation (8) provides a criterion to evaluate the performance of the algorithm. Apart from giving an analytical solution, numerous steepest descent strategies are proposed to obtain the optimal weight vector. The k-th iteration of weight vector can be written as

$$\mathbf{w_k} = \mathbf{w_{k-1}} - \boldsymbol{\mu}\frac{\partial \mathbf{J}}{\partial \mathbf{w_{k-1}}} \quad (9)$$

where $\mu$ represents the step size which is a positive constant. Apparently, the convergence of the Block LMS algorithm is mainly determined by the value of step size.

The weight vector update equation is [7]

$$\mathrm{w_k} = \mathrm{w_{k-1}} - \mu \sum_{i=0}^{M-1} \mathrm{u}(\mathrm{kM}+\mathrm{i})\mathrm{e}(\mathrm{k}+\mathrm{i}) \quad (10)$$

where M is the block size, and n can be decomposed as $\mathrm{n} = \mathrm{kM} + \mathrm{i}$. As an averaging error accumulated in each data block, it is used to optimize the adaptive filter's parameters. The Block LMS algorithm has a better ability to enhance the desired signals which improves the performance of the mini radar system.

To validate the performance of the Block LMS algorithm, a sinusoidal signal contaminated by the Gaussian noise is generated and the SNR of the input signals varies from -15 dB to 5 dB. Fig. 5 presents the performance of the four adaptive algorithms. Compared with the other algorithms, the Block LMS algorithm is the most suitable method to cope with the echo signals obtained by the radar when it works in the complex environment.

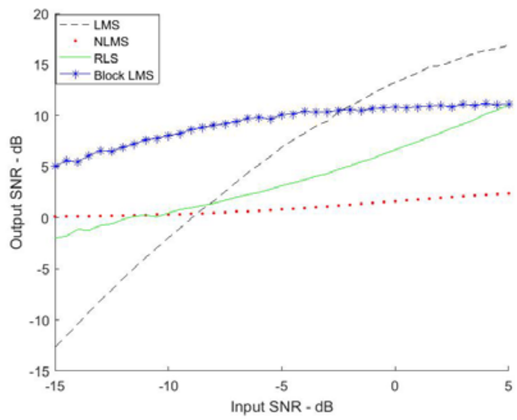


Fig. 5 Comparison of different algorithms

## IV. Experiment

The experiment described in this section is designed to present the performance of the mini radar system. Mini radar system is equipped with a Next Unit of Computing (NUC) which is designed by Intel. The NUC with the $5^{th}$ generation Intel Core i7 processor can satisfy the requirement for fast arithmetical operation. Furthermore, to optimize the math routines, Intel Math Kernel Library (Intel MKL) has been used to accelerate the computation about Fast Fourier Transform and vector operations. The control system is developed using C++ and it communicates with the application terminal through the connection of WIFI.

The radar system is placed in the broad field where there should be no higher obstacle around it. Since the beam-width of the pyramidal horn antenna is small, the angle between antennas and the horizontal plane is 45° to facilitate the measurement. Additionally, physical isolation has been employed to reduce the interference. For the radar front end, frequency modulated waves ranged from 14.5 GHz to 15.5 GHz are emitted, and the sampling rate can be set as 20 MHz.

To imitate the actual situation, Phantom 3, a consumer-grade UAV designed by the DJI, is used in our experiments. Fig. 6 displays its appearance, and its diagonal distance excluded the airscrews approximates to 0.35 m. The UAV flies in front of the radar, and its velocity controlled by the remote controller approximates to 3 m/s.

Fig. 7 exhibits the track of the UAV that has not been processed by the Block algorithm. The continuous curve in the figure is the trajectory of the UAV, and the light-colored discontinuous spot represents the noises existed in the signals. Fig. 8 displays the track of the UAV which is processed by the adaptive algorithm. Compared with the original data, the outcomes of the processed signals are cleaner and easier to distinguish. And targets can be extracted in the use of the peak-search algorithm.

Fig. 6 The diagram of Phantom 3 (provided by DJI)

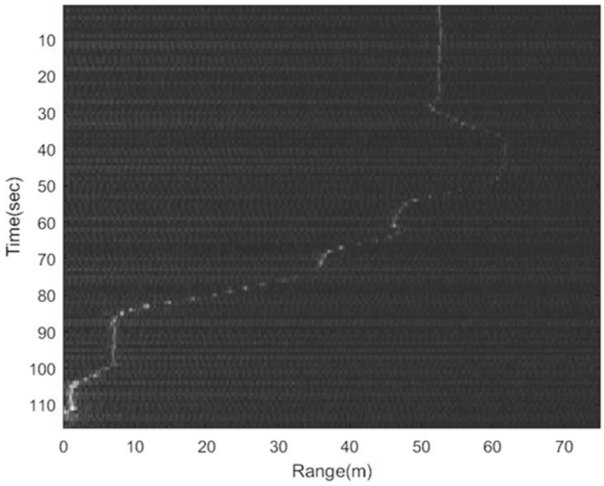


Fig. 7 The track of UAV without Block LMS algorithm

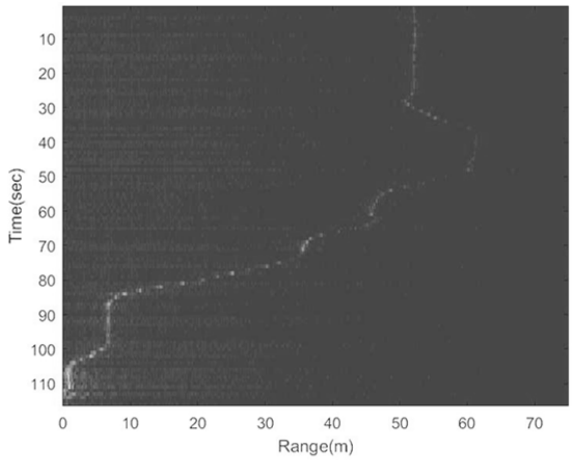


Fig. 8 The track of UAV with Block LMS algorithm

## V. Conclusion

In this paper, we demonstrated a mini radar system designed to detect UAVs and its major components. The experimental results not only indicate the feasibility of the radar system but reveal the effectiveness of the data processing algorithm.

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