Graphic User Interface Development of a Digital Phased Array Radar System

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Abstract. A graphical user interface (GUI) of a digital phased array radar system is developed to detect and reveal the supposed multi-targets. As the core of the digital radar system, the radar signal generation environment aims at producing a radar echo signal, which is achieved by superposing the simulated radar transmission signals, clutter, jamming signals and radar internal noise linearly; And the radar signal processing environment focuses on processing the radar echo signal to measure multi-target range and velocity information, by employing pulse compression (PC), moving target indication (MTI), moving target detection (MTD) and constant false alarm rate (CFAR) technologies. Every module of the core can be exhibited in the form of MATLAB GUI. In addition, an integrated GUI of the digital phased array radar system is constructed to offer all the multi-target detection and display functions.

1. Introduction

Nowadays, the performance evaluation of a radar system implemented with traditional methods becomes much more difficult, whereas the semi-physical or all-digital simulation method can be an alternative option to accomplish the system design and evaluation. The phased array radar technology has been popular with most countries in the past years, as a development trend of modern radars [1-2]. Based on the establishment of radar signal generation and processing environments, simulation GUls of the digital phased array radar system are prepared to develop and operate.

A variety of radar simulation GUls have been developed by previous researchers. Li et al. presented and designed a simulation system of phased array radar based on Simulink, and studied the key techniques of composition, modeling and exploitation of modules [3]. Wang et al. studied and simulated the phased array radar system by using MATLAB/Simulink as the simulation platform, and their simulation module library included the antenna, signal generation and processing, and GUI man-machine interface modules [1]. Raja et al. designed a GUI in MATLAB to model the ambiguity function, in order to derive the target parameters from the received signal [4]. Collazos et al. presented the implementation of a GUI for a small radar system, and the GUI was built using three different platforms: MATLAB, Octave and Java [5]. Yan et al. set up a kind of MATLAB simulation and analysis system of real-time data communication, and recorded playback based on transport control protocol/Internet protocol and GUI [6]. Yao pointed out the superiority of the SystemVue software for the radar system simulation, and used the software to build up the simulation model of receiving system network [7]. However, few simulation GUls were specially designed for the phased array radar.

In this paper, a comprehensive GUI is designed for the digital phased array radar system on the basis of radar signal generation and processing environments. Both the radar signal generation and processing environments have various sub-modules, whose GUls are devised respectively. By
operating the radar simulation system, not only the radar echo signal can be generated and processed, but also the detected multi targets can be displayed on the radar search interface.

2. Radar signal generation

We established a radar signal generation environment in [8], which was the front-end of a digital phased array radar system. This environment could model and simulate radar transmission signals, clutter and jamming signals, as well as radar internal noise. And the radar echo signal can be resulted from combining these signals linearly.

2.1. Radar transmission signal

Radar transmission signals are mainly coherent pulse train waveform, LFM signal, stepped frequency waveform, phase-coded waveform, M-sequence code waveform and Barker code waveform, as well as linear FMCW waveform. However, the LFM signal is commonly used as the transmission signal. The reason is that the matched filter used later is insensitive to the Doppler shift. Even if the echo signal has a larger frequency shift, the identical filter can be applied to accomplish the pulse compression. The LFM signal can be expressed as

\[ s(t) = A u(t) \sin \left[ 2\pi \left( f_0 + \frac{1}{2} \frac{k}{T} \right) t \right], \quad |t| \leq \frac{T}{2} \]  

where \( k = \frac{B}{T} \) is modulated frequency, in which \( B \) is signal bandwidth and \( T \) is pulse width; \( f_0 \) is initial frequency related to the initial phase; modulated function \( u(t) \) is a rectangle pulse train. The time domain waveform of LFM signal is shown in figure 1.

2.2. Clutter signal

The clutter in a resolution unit was composed of a number of scatterers. The phase and amplitude of these scatterers are stochastic, and probability distribution functions can therefore be leveraged to describe the clutter statistically. The types of these functions are determined by characters of the clutter itself, grazing angle and radar operating frequency.

Typically, there are Rayleigh, lognormal, Weibull and \( K \) distribution clutters. Take the lognormal distribution clutter for example, and the lognormal distribution can describe the ground clutter with a low grazing angle and the high-resolution radar sea clutter. It can be formulized as:

\[ f(x) = \frac{1}{\sqrt{2\pi} \sigma_x} \exp \left[ -\frac{\ln^2 \left( \frac{x}{u_m} \right)}{2 \sigma_x^2} \right], \quad x > 0, \sigma_x > 0, u_m > 0 \]  

where \( u_m \) is scale parameter, meaning the distribution mean; \( \delta_c \) is form parameter, representing the distribution gradient. The simulation result of this clutter is shown in figure 2.

2.3. Jamming signal

Radar jamming is the technical name of destroying and hindering normal operation of the enemy’s electronic and radar equipments. It makes the radar unable to detect and trace the true targets correctly, in order to disturb the radar’s working. In terms of jamming energy source, radar jamming falls into unintentional and intentional jamming. And intentional jamming is divided into active and inactive jamming based on transmitting electromagnetic signals or not. In addition, active jamming splits into masking and deception jamming.

According to producing way of the masking noise signals, active masking jamming can be classified into four kinds: radio frequency (RF) noise jamming, noise amplitude modulated (AM) jamming, noise frequency modulated (FM) jamming, and noise phase modulated (PM) jamming. And deception jamming can divide into range deception jamming, velocity deception jamming, angle deception jamming, and AGC deception jamming, as well as multi-parameter deception jamming. Take the RF noise jamming for example, and it is the jamming that magnifies and transmits the narrowband Gaussian noise directly, also called direct noise amplifier. The equation of narrowband Gaussian noise is:
where envelope function $U_n(t)$ obeys the Rayleigh distribution; phase function $\varphi(t)$ obeys the $[0, 2\pi]$ uniform distribution, independent of $U_n(t)$; carrier frequency $\omega_j$ is a constant and much larger than the bandwidth of $J(t)$, and $J(t)$ is generally formed through filtration and amplification of a low-power noise. Figure 3 represents time domain waveform and frequency spectrogram of the RF noise jamming signal.

### 2.4. Radar echo signal

In the simulation process, the noise of the phased array radar itself is treated as a Gaussian white noise. And this noise also needs to be added to the received echo signal, which can be produced by a built-in random function of MATLAB. In the paper, three point targets are supposed to be searched by the phased array radar. Table 1 enumerates their own initial movement parameters.

| Target  | Range (m) | Velocity (ms$^{-1}$) |
|---------|-----------|-----------------------|
| True 1  | 15000     | 300                   |
| True 2  | 20000     | -100                  |
| True 3  | 13000     | -200                  |

The radar echo signal achieved by superposing radar transmission signal, Gaussian white noise, lognormal distribution clutter and RF noise jamming linearly is shown in figure 4.

### 3. Radar signal processing

Then a radar signal processing environment was structured in [9] and [10], to measure multi-target range and velocity information, as well as detect the supposed targets. We adopted PC, MTI, MTD
and CFAR technologies to process the radar echo signal produced in the radar signal generation environment.

3.1. Pulse compress
When employing very short pulses, the radar range resolution can be improved greatly. However, this will lower the average transmission power, and prevent the radar from operating normally. Therefore, a suitable range resolution will be available when increasing the pulse width. It is the PC technology that can make this trade off. PC can not only improve the signal-noise ratio, but also acquire a higher range resolution. There are two methods to implement the PC, i.e. the time domain method and frequency domain method.

Take the frequency domain method for example, and its basic principle is as follows: The fast Fourier transform (FFT) is applied to the radar echo signal and the signal spectrum $S(w)$ is obtained; $S(w)$ is multiplied with its filter’s frequency response function $H(w)$; the inverse fast Fourier transform (IFFT) is used to process again and output the compressed signal sequence $y(n)$. The entire process of the frequency domain method can be expressed as

$$y(n) = \text{IFFT}[S(w) \cdot H(w)] = \text{IFFT}[\text{FFT}[S(n)] \cdot \text{FFT}[H(n)]]$$  \hspace{1cm} (4)

The PC signal using the frequency domain method is portrayed in figure 5.

3.2. Moving target indication
The MTI filter can suppress some target-like echoes produced by clutters and help moving target echoes pass the filter without loss. However, the clutter spectrum generally centers at zero frequency and integral multiples of the radar pulse repetition frequency (PRF), and has a small-scale extension. In order to suppress the clutters, a filter should be devised with a deep stopband locating at zero frequency and integral multiples of the radar PRF. The MTI filter can be constructed through delay lines. This filter’s frequency response should be periodic, with the zero value at integral multiples of the PRF. As a result, the targets whose Doppler frequencies are integral multiples of the PRF will experience very large attenuation.

The single and double delay cancellers are commonly used as the MIT filters. Take the double delay canceller for example, and it is also called three-pulse canceller, whose difference equation is

$$y(n) = x(n) - 2x(n-1) + x(n-2)$$  \hspace{1cm} (5)

Figure 6 shows the processing result of the double delay canceller.

3.3. Moving target detection
MTD is a more effective frequency-domain filter technology, which is developed on the basis of MTI. Since MTI has a poor capability of suppressing fixed clutters and slowly moving clutters, a narrow-band Doppler filter bank should be connected after MTI processing. This filter bank covers the whole repetition frequency range, and it can detect moving targets. In other words, it is equivalent to accumulating different channels coherently.

The coherent accumulation can be expressed as

$$y(n) = \sum_{l=0}^{N-1} w_l x(n - lT_r)$$  \hspace{1cm} (6)

where $T_r$ is the radar repetition period, $N$ is the accumulated pulse number, and $w_l$ is the weight coefficient. $w_l$ varies regularly for every return as

$$w_{lk} = \exp(-j2\pi lk / N) \quad l = 0, 1, \cdots, N-1$$  \hspace{1cm} (7)

where $l$ is the $l$-th coefficient output, and each $k$ represents a different weighting value corresponding to a different Doppler filter response.

There are two implementation methods for narrow-band Doppler filter banks. One is adopting FIR filter banks in the time domain; the other is using DFT or FFT in the frequency domain. Here take the latter method for example, as it is much simpler to implement the filter banks. The MTD result after using FFT processing is shown in figure 7.
3.4. Constant false alarm rate

The CFAR detection technology aims at offering a detection threshold to avoid the effect of noise and jamming variations, and enabling the targets to have a constant false alarm probability. Two classic CFAR detection methods were studied and emulated in [10]. They are the mean level (ML) and ordered statistics (OS) CFAR detectors.

In addition, ML CFAR can be classified as cell average (CA) CFAR, greatest of (GO) CFAR, and smallest of (SO) CFAR, etc. Take the GO CFAR for example, and this CFAR detector is able to exhibit a good performance in a clutter edge environment. The larger power of the front and rear sliding windows is treated as estimate of the background clutter power, which can be expressed as:

\[ Z = \max(X,Y) = \max\left(\sum_{i=1}^{n} x_i, \sum_{j=1}^{m} y_j\right) \] (8)

The false alarm probability of GO CFAR detector can be derived as:

\[ P_{fa,GO} = 2(1 + T)^n - 2 \sum_{i=0}^{n-1} \binom{n+i-1}{i} (2 + T)^{-(n+i)} \] (9)

Equation (9) indicates that, the nominal factor \( T \) is a constant only determined by \( P_{fa,GO} \) and \( n \). The simulation results of the Go CFAR detector is shown in figure 8.

4. Radar simulation system operating

After completion of the radar signal generation and processing environments, a simulation GUI can therefore be developed for the phased array radar system. As is shown in figure 9, the radar simulation GUI of MATLAB is mainly composed of simulation controls, parameters setting, radar displays and modules library.
4.1. GUI components

- Simulation controls. There are three basic buttons, i.e. “Start”, “Reset” and “Exit”. “Start”: run the digital phased array radar system; “Reset”: reinitialize the radar simulation system; “Exit”: close the simulation system.

- Parameters setting. Radar, target, and simulation system parameters all need setting. One can adjust these parameters through this GUI, or use default parameters of the background programs directly for simplicity.

- Radar displays. The main radar display employs the phased array antenna to scan all over the space, and the detected multi-targets will be presented on the radar search interface, as shown in figure 10. And the mini map reveals not only the real position of simulation targets, but also the multi-target movement trend in real time (see figure 11).

- Modules library. This library contains the phased array antenna, transmission signal, clutter, jamming, return signals, pulse compression, MTI, MTD, and CFAR module, etc. These modules can be emulated to provide time domain and spectrum graphs.

4.2. Operating mode

The working procedures of the digital phased array radar system are given as following.

- **Step I.** Set parameters, including antenna, transmission signal, clutter, CFAR and target parameters, etc. These can be encapsulated in the background programs as default parameters.

- **Step II.** Click the “Start” button to run the radar simulation system. The transmitter is activated to generate the radar transmission signals, and the receiver will collect the radar echo signals. These echo signals are processed in sequence by pulse compression, MTI, MTD and CFAR technologies to extract the target signals. The ultimate target signals enable to measure range and velocity information, and display the detected multi-targets on the radar search interface.

- **Step III.** Continue scanning, and repeat **Step II**, until reset or exit the radar simulation system. If click the “Reset” button, all the parameters are initialized, and the system is prepared to conduct a new simulation test.

- **Step IV.** If the simulation result is different from the practical application, each module in the library can be analyzed and tested to find out the potential problems. After overcoming them, performance of the digital phased array radar system is considered to approximate the actuals.
5. Conclusions
In this paper, a MATLAB GUI is developed for the phased array radar system, with the phased array antenna element, radar signal generation and processing environments all embedded. These integrated modules also have their own GUIs to process all kinds of signals. When operating the radar simulation system, the detected multi-targets will be revealed on the radar search interface. In the future, the angle measurement module will be paid much attention to enrich the module library.

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