Simulation Analysis Of Real-Time Signal Processor For Pulse Doppler Radar

M.Bala Bhanu, P.Deepthi, K.V.Ramana Rao

Abstract: With the advancements of VLSI chips and powerful computational devices, new complex algorithms and systems are being devised to tap the available computational power and to get the maximum performance. One particular system is the signal processor of Pulse Doppler Radar. This paper aims at finding the range and radial velocity of a moving target using Pulse Doppler Radar for land surveillance. Different optimization techniques have been employed to increase the accuracy of the system. The design was tested on MATLAB for software verification.

Keywords: Phase coding, Pulse compression, Fast Fourier Trans- form, Field Programmable Gate Array, Additive White Gaussian Noise, Pulse Repetition Frequency.

I. INTRODUCTION

Radar (Radio Aid to Detection and Ranging), as the name implies, is a device used to detect and locate objects by using electromagnetic waves. The basic principle of radar is that objects partially reflect electromagnetic waves. But the actual task is to extract the required information from the received signal filled with clutter and noise. Earlier radars were built primarily for military purposes and provided only this basic functionality. Modern radars use the same basic principles as the earlier radars but the signal processing techniques and algorithms used for data analysis have improved significantly over the decades [1]. Rapid improvements in digital technology have enormously improved the computational capabilities of the available de- vices. This has motivated researchers to develop complex algo- rithms for signal processing in radar. This paper discusses the design of Pulse Doppler Radar which is intended for ground surveillance of moving targets. It determines the range as well as the radial velocity of the targets. Different algorithmic enhancements like pulse compression and windowing function have been employed to increase the accuracy of the system. The data input to the designed system is arranged in a way that makes the performance of computational algorithms easy. Moreover, a pipelined architecture has been presented in order to extract the maximum throughput from the system using minimum resource utilization. The rest of the paper is organized as follows. The following section discusses the system parameters that have been used. Section III describes the signal processing techniques used for retrieving the required information from the given signal. Section IV discusses the simulation results and section V gives the details of hardware implementation on FPGA. Section VI concludes this paper.

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II. SYSTEM MODEL & PARAMETERS

For implementing the radar signal processing part, certain radar parameters have to be defined. Since it is a pulsed radar, it will transmit a short pulse and listen to the echoes for the remaining time [2]. We have assumed that a duplexer has been employed; and the receiver and transmitter use the same antenna. Pulse Repetition Frequency (PRF) and Pulse Repetition Interval (PRI) dictate critical parameters such as the maximum unambiguous range, maximum Doppler frequency etc. The PRI = 1 ms (PRF = 1 KHz) has been assumed since it is a medium PRF Radar. On the other hand, minimum range, range resolution and the energy transmitted is defined by the pulse width of the transmitted pulse. The 1% duty cycle is assumed, i.e. pulse width of 10 µs for the pulse duration of 1 ms. Radar cross section (RCS) gives information about the fraction of incident energy reflected back by a specific kind of target and hence the detectability of a specific target. It depends on factors including the absolute size of target, target material and shape of the target [1]. As the focus is on land surveillance, the average RCS we have considered is that of an automobile (or a truck) which is 100 m^2 (200 m^2). The sampling rate is dictated by PRF, pulse width and the reference pulse used for transmission. Moreover, it must also satisfy the Nyquist criterion. After calculation, the sampling frequency has been decided to be 1 MHz. Few other parameters can be seen in Table I.

TABLE I
RADAR SYSTEM PARAMETERS

Parameter	Value
Maximum Range (R_{max})	150 km
Average Power (P_t)	10 KW
Sampling Frequency	1 MHz
Carrier Frequency (f_c)	1 GHz (L-Band)
Radar Cross Section (RCS)	100-200 m^2

The maximum range that our radar can measure without ambiguity is defined by,

$$R_{un} = \frac{cT_p}{2}$$

where T_p is the pulse repetition interval (PRI). With the PRI of 1 ms, the maximum range comes out to be 150 km, which is reasonable for long range land surveillance. Similarly, the minimum range is determined by the width of the pulse, during which the receiver is not listening to the echoes and is given by [2],

$$R_{min} = \frac{c\tau}{2}$$

where pulse width τ of 1 µs gives the minimum range of 1.5 km. In order to measure the radial velocity of the target, the Doppler shifts produced by the targets need to be processed. To account for approaching as well as the retreating targets, the maximum allowable Doppler is half of the PRF which comes out to be 500 Hz. Using the following equation, we can calculate the maximum measurable radial velocity [1]:

$$v_r = \frac{cf_d}{2f}$$

where f_d is the Doppler frequency shift, f_c is the carrier frequency and v_r is the radial velocity. In our case, the maximum velocity is 75 m/s.

III. SYSTEM DESIGN

The received signal at the input of the system is given by,

$$r(t) = A(t)\sin(2\pi f_c t + \theta(t))$$

where A(t) is the constant amplitude pulse envelope and θ(t) is the phase component which may or may not be constant depending on the reference pulse used. The received signal has to go through a number of signal processing stages, after which we are able to extract the required information. The figures of merit used in determining the performance of the radar include the probabilities of detection and false alarm, range resolution and side lobes in case of multiple targets. The range resolution determines how much we can distinguish between two closely spaced targets. The issue of side lobes comes into play when one target with a strong echo signal masks the detection of another target with a weak echo signal [2]. These two parameters are dependent on the waveform that the radar transmits. Also affecting the performance is the signal to interference ratio (SIR). The block diagram of the signal processing techniques operated on the received signal is shown in figure 1. Each block is discussed in detail.

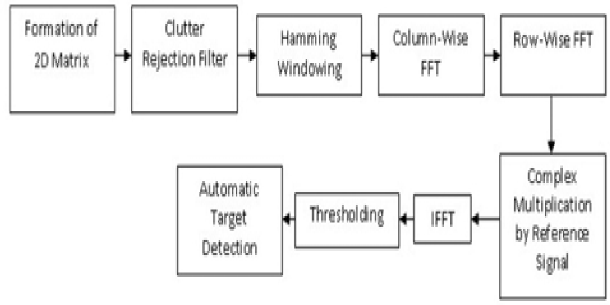


Fig. 1. Block Diagram

A. Formation of Data Matrix

In Pulse Doppler radars, the received data is not processed sample by sample, or even pulse by pulse. Rather, several pulses and samples are combined to form a data matrix so that operations can be performed on them altogether. Each column of the data matrix represents a specific range bin in all the pulses and each row represents all the range bins of a specific pulse [2], [3]. The number of columns of the matrix is equal to the number of samples taken in each pulse. Whereas, the number of rows determined by the number of range bins. A typical arrangement is shown in figure 2. In our case the dimensions of the data matrix are 128×1024.

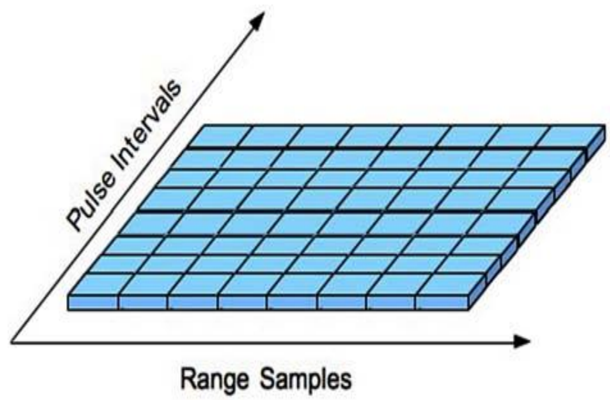


Fig. 2. Data Matrix

B. Clutter Rejection Filter

The clutter for a radar system can be different for different radars. In our case, stationary environment is modeled as clutter. To get rid of it, Three Pulse Canceller has been used [1] as shown in figure 3. It is a simple FIR filter and its transfer function is given by:

$$H(z) = 1 - 2z^{-1} + z^{-2} \quad (1)$$

This clutter rejection filter has been applied along the columns of the data matrix because a column represents a specific range bin in different pulses and the clutter remains same from pulse to pulse.

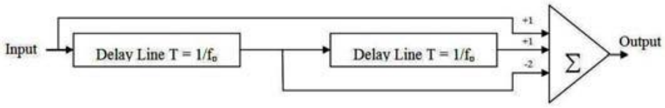


Fig. 3. Three Pulse Canceller

C. Windowing Function

Three pulse canceller while eliminating the clutter, also introduces side lobes. The purpose of windowing is to truncate the infinite duration impulse response and reduce the side lobes in the frequency domain. With reduced side lobes, the detection of targets is improved. We chose the Hamming window, because it significantly reduces the side lobes in our case [4].

D. Doppler Processing

Once the Hamming window has been applied, we take the FFT (Fast Fourier Transform) along each column (specific range bin) to obtain the velocity information of targets present in that range bin. If there are two or more targets present at the same range with sufficiently different velocities, they will be separated by this step [2]. This step provides complete information regarding the Doppler shift of all the targets present.

E. Pulse Compression

The range resolution of the radar depends on the width of the pulse. The shorter the pulse, the better will be the resolution. At the same time, detection performance is improved with longer pulse duration which requires more transmitted energy ($A^2 \tau$). Our goal is to extract maximum range resolution while spending minimum energy. However, increasing the transmitted energy (longer pulse width) means degrading the range resolution. Pulse compression is a technique, using which we can get improved detection performance without compromising on range resolution. We can get the resolution of a short pulse with the energy of long pulse. The major advantage of this technique is that it requires less peak power, which is expected of a good radar system design [5]. There are two major techniques used to achieve pulse compression; Linear Frequency Modulation (LFM) chirp and Phase Coding. We have used Binary Phase Coding in our system. More specifically, 11 chip Barker code sequence has been used in our reference pulse and is shown in figure 4.

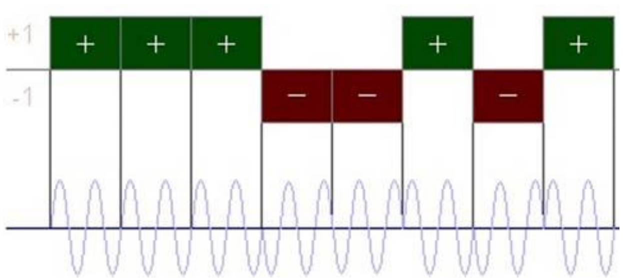


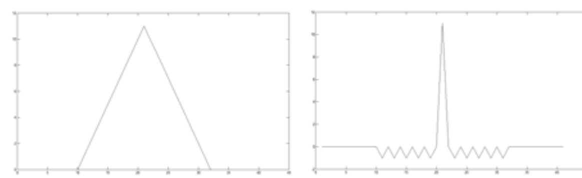
Fig. 4. 11 Chip Barker Code

Using pulse compression, the target detection is done by finding the peaks above the set threshold generated due to the cross correlation of received signal with the reference pulse. In this case, range resolution depends upon the reference pulse. The higher the bandwidth of the signal, the better will be its range resolution as dictated by the following formula,

$$\Delta R = \frac{c}{2\beta} \qquad (2)$$

where β is the bandwidth of Reference Pulse.

We noted that the improvement gained depends upon the autocorrelation of the reference pulse. The sharper the auto- correlation of the pulse better will be the range resolution. Auto correlation of rectangular pulse and barker code of same length is shown in figure 5(a) and 5(b) respectively, which clearly show the improvement that can be attained using barker code.



(a) (b)

Fig. 5. Comparison of Auto-correlation of Rectangular Pulse and 11 chip Barker Code

F. Range Processing

Once Doppler processing has been done, the data matrix can be processed to extract the ranging information of the targets. The received signal is processed using matched filtering. To do so, cross correlation between received signal and reference pulse is taken in the frequency domain. The Hamming window is also applied by multiplying it with the reference pulse to reduce the side lobes along the rows. At the end, IFFT is taken to bring it in the time domain.

G. Thresholding and Target Detection

After passing through the above operations, the data matrix is subjected to a threshold. The values below the threshold are considered as noise and hence discarded [1]. However, the values above the threshold do not necessarily represent a target. Rather we need to find the point with the highest amplitude in the peak to determine the correct range and velocity. For automatic detection, we have designed an algorithm that searches for peaks by comparing it with its neighboring elements. It avoids multiple target detection by first checking for target's existence in the vicinity in range dimension and then in the velocity dimension. If the target is not found in both domains and is itself the tip of a peak, then it is regarded as a new target. Although each target peak has been detected but no actual velocity and range values have been extracted yet. To obtain the velocity and range measurements we used the row and column number to scale the final values appropriately.

IV. SIMULATIONS

Since our focus was on the signal processing part, we have generated a test data for which simulation has been done. We assumed 3 constant velocity and 1 accelerating targets. Further, we assumed that one of these targets is approaching while the rest of them are moving away. The range and velocity data for these targets is given in table II.

TABLE II
TARGETS & THEIR SPECIFICATIONS

Targets	Starting Range	Velocity	Acceleration
Target 1	100	15	Nil
Target 2	100	30	Nil
Target 3	400	-45	-0.1
Target 4	500	60	Nil

The transmitted pulse was shifted and scaled for each of the targets separately on the basis of their respective ranges. These shifted pulses were then accounted for velocity by adding Doppler shift in their return echoes using following expression:

$$f_d = \frac{2 v_f f_c}{c} \quad (3)$$

where $v_f = v_i + \alpha \times \frac{rep}{10}$

We have incorporated Rayleigh fading for each of the return echoes. The parameter α for Rayleigh random variable is specified taking into account the range of the target. A stationary target at the range of 45 km has been placed to simulate the effect of clutter rejection filter. Also, additive white Gaussian noise (AWGN) has been added to account for receiver noise introduced in actual systems.

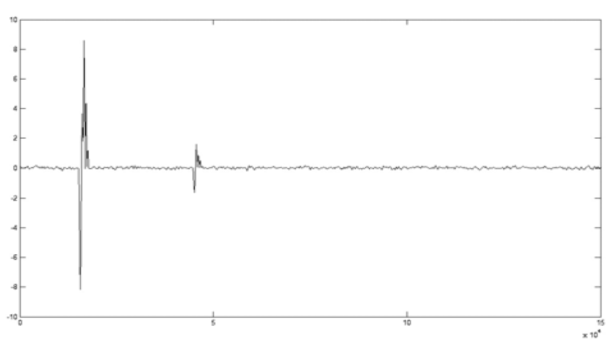


Fig. 6. Received Signal

The received signal is shown in figure 6. Apparently, there seem to be two targets present in the received signal. But after matched filtering and Doppler processing to extract the range and velocity information, the scaled results are shown in the figure 7 which clearly shows the presence of four targets as generated by test data. To show the computational verification of the above block diagram, snapshots of operations on a 8 by 8 data matrix has been shown in figure 9. The hardware results complies with the MATLAB results. The whole operation was completed in less than 90 µs.

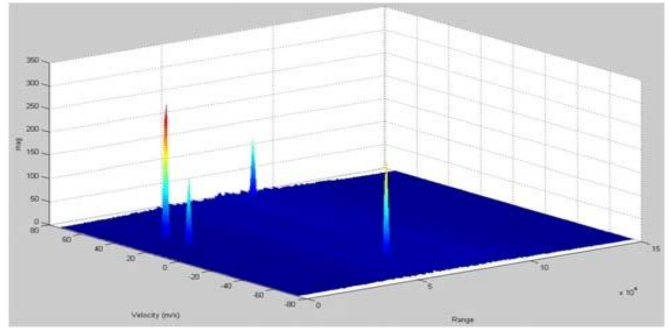


Fig. 7. Final Output after Range & Velocity Processing

VI. CONCLUSION

In this paper, Pulsed Doppler Radar signal processor for land surveillance using MATLAB. A pipelined architecture is presented along with a series of software and hardware optimizations of signal processing techniques includ- ing Hamming window, matched filter for range processing and Doppler processing for velocity extraction. The software implementation hardware performance complies hardware performance in terms of computation and is highly efficient in terms of resource utilization.

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