Generalized Approach to Signal Processing in Noise for Closing Vehicle Detection Application Using FMCW Radar Sensor System

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Abstract: *We discuss the main principles of signal detection and signal processing algorithms employed by the 24 GHz frequency modulation continuous wave (FMCW) radar sensor systems under closing vehicle detection (CVD). This research deals with designing the detection and signal processing algorithm for FMCW radar sensor based on the generalized approach to target return signal detection and processing in noise and interference.*

1. Introduction

Total safety approach means that the vehicle must have to avoid accidents and prevent injuries. This approach is achieved by integrating environmental sensors to build a network of active and passive vehicle safety systems. The closing vehicle detection (CVD) is defined as a detection of closing vehicles in one or several rear zones. As a result, a warning is sent to the driver. The closing speed of a target vehicle is defined as a difference between the target and the subject vehicle speeds [1]. This definition applies to target vehicles in the rear zones only. The frequency modulation continuous wave (FMCW) radar sensor with 24 GHz operation frequency seems to be the most suitable technology for middle range (MRR) and short range radar (SRR) applications [2]. Any radar system takes a decision about the presence or absence of targets after cancelling the interference and noise caused by various sources. The basic operations performed by the signal and data processors are the detection of targets and extraction of information from the target return signal to determine a wealth of relevant parameters of the targets such as the target range, position, and velocity. The target return signal detection and processing algorithm should offer the high range resolution, interference and noise cancellation capabilities to eliminate the false alarm probability. In this paper, the proposed generalized approach (GA) to signal processing in noise allows us to formulate a decision-making rule about the presence or the absence of the target vehicle based on the definition of the jointly sufficient statistic of the likelihood function mean and variance with complete compensation of noise components and interferences. The results demonstrate the high detection performance, accuracy of definition and resolution of signal parameters.

2. Generalized Approach to Signal Processing in Noise:

The main idea of this approach is based on an introduction of additional noise source (the reference noise), which does not carry any information about signal parameters, and a combination of the Neyman-Pearson (NP) detector that is optimal for detection of deterministic signals with known parameters and the energy detector that is optimal for detection of deterministic signals with unknown parameters, in order to improve the detection performance of FMCW radar system [3]. This combination allows us, firstly, to take into consideration such a very important statistical parameter as a variance of the likelihood function, and, secondly, to formulate a decision-making rule about the presence or the absence of the target vehicle based on a definition of the jointly sufficient statistic of the mean and variance of likelihood function. There is a need to note that a decision-making rule about the presence or the absence of the target vehicle of the NP and energy detectors is made based on the definition of the sufficient statistic of the likelihood function mean only.Thus, we have an additional information by the sufficient statistic about the likelihood function variance in the case of the generalized approach.

Let $X(t)$ be the input stochastic process, which is observed within the limits of the time interval [0,T]; $a(t)$ is the target return signal; $\xi(t)$ is the additive Gaussian noise with zero mean and the known variance σ_{ξ}^{2} .The initial condition of the target vehicle detection problem can be presented in the following form:

$$X(t)=\begin{cases} a(t)+\xi(t) \Rightarrow H_1 \\ \xi(t) \qquad\qquad \Rightarrow H_0 \end{cases} \tag{1}$$

where H_1 is the hypothesis about the presence of the target vehicle; and H_0 is the alternative hypothesis. Using the elements of the observed input stochastic sample X_i, the decision-making rule about the presence or the absence of the target vehicle of the generalized approach can be represented in the following form:

$$\begin{cases} 2\sum_{i=1}^{N} X_i a_i^* - \sum_{i=1}^{N} X^2{}_i > K_g \Rightarrow H_1 \\ 2\sum_{i=1}^{N} X_i a_i^* - \sum_{i=1}^{N} X^2{}_i \le K_g \Rightarrow H_0 \end{cases} \tag{2}$$

where K_g is the threshold, and $a^*(t)$ is the model signal generated by the model signal generator (MSG) of the generalized detector (GD). The basic structure of the generalized detector (GD) is presented in Fig. 1 [4].

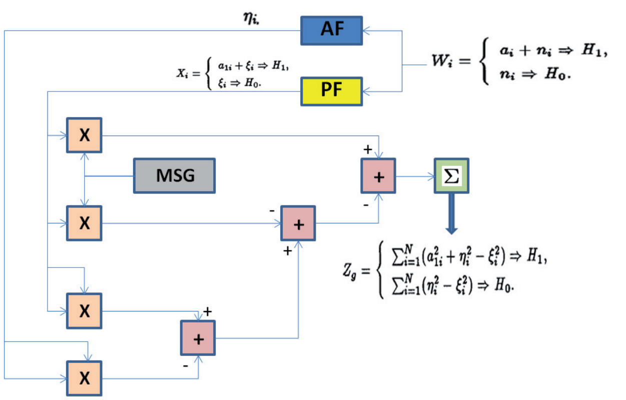

Figure 1. Generalized detector.

It is supposed that there is a frequency–time region of interferences with ‘‘yes’’ signal, and there is a frequency– time region of interferences with ‘‘no’’ signal that is known a priori. This modification makes it possible to perform a theoretical idea of the generalized signal detection algorithm. Two uncorrelated samples are used. One of the two is a reference sample as it is known a priori that there is ‘‘no’ ’signal in this sample. This fact allows us to obtain a jointly sufficient statistics of mean and variance of the likelihood function [3].

The background noise forming under the use of GA is generated by two linear systems that can be presented, for example, as band pass filters, namely, the preliminary filter (PF) with the impulse response $h_{PF}(\tau)$ and the additional filter (AF) with the impulse response $h_{AF}(\tau)$. The incoming signal cannot pass through the AF. Thus, the received signal and noise can be appeared at the PF output and only the noise is appeared at the AF output. If the Gaussian noise comes in at the AF and PF inputs, the noise forming at the AF and PF outputs is Gaussian, too, because AF and PF are the linear systems, and the noise take the following form:

$$\xi_{PF_i}(t) = \int_{-\infty}^{\infty} h_{PF}(\tau) n_i(t-\tau) d\tau \quad \text{and} \quad \xi_{AF_i}(t) = \int_{-\infty}^{\infty} h_{AF}(\tau) n_i(t-\tau) d\tau \ . \tag{3}$$

In the case of signal absence in the input process, the statistical parameters at the AF and PF outputs will be the same under the condition that these filters have the same amplitude-frequency responses and bandwidths by value, because the same noise is coming in at the AF and PF inputs. The output of the PF is shown in Fig. 2, when we have only noise in the input and also when we have target return signal with additive noise.

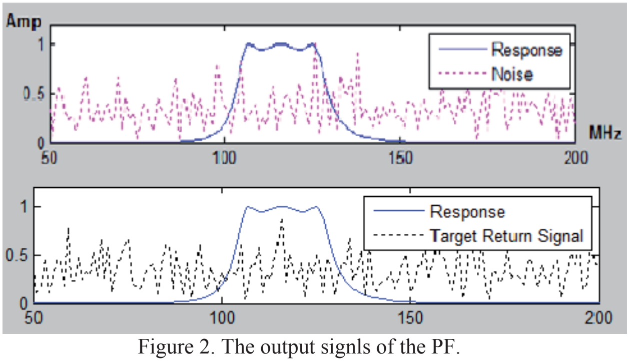

Figure 2. The output signls of the PF.

The generalized signal detection algorithm can be presented in the following form:

$$\sum_{i=1}^{N} 2X_i a_i^* - \sum_{i=1}^{N} X_i^2 + \sum_{i=1}^{N} \eta_i^2 > Kg, \tag{4}$$

The first term corresponds to a synthesis of the detector correlation channel with twice the gain, and considers as a sufficient statistic for the mean (priori information). The second term corresponds to a synthesis of the detector autocorrelation channel connected with the PF, and considers as a sufficient statistic for the variance (energy detector with no priori information). The third term corresponds to a synthesis of the detector autocorrelation channel connected with the AF (noise power) [5].

Using the AF jointly with the PF improve the processing method of the background noise in the generalized detector. Background noise is a difference of energy characteristics of interferences at the PF and AF outputs. This difference tends to zero in the root-mean-square sense:

$$n_g(t) = \eta^2(t) - \xi^2(t). \tag{5}$$

The presence of additional information about the statistical parameters of the likelihood function leads to better qualitative characteristics of signal detection in comparison with the optimal signal detection algorithms of classical and modern theories [6].

3. Simulation Results

FMCW radar sensor system uses a transmitted waveform called a linear frequency modulated FM wave (or it is called chirp wave), where the frequency is swept linearly with the time. In general, when the target vehicle has a relative velocity, the transmitted waveform should consists of two sweeps, the up-sweep and the down-sweep. This special waveform shape is used to eliminate the ambiguity of the target vehicle range and velocity. The up-sweep part of the transmitted signal is defined in the following form:

$$T_{up}(t) = \cos\left[2\pi\left(f + \frac{1}{2}\frac{B}{T_c}t\right)t\right], \tag{6}$$

where f is the transmission frequency or the FMCW radar sensor system operation frequency; B is the sweep bandwidth; and T_c is the sweep time. The basic idea is to generate a linear frequency ramp with bandwidth B (for a single ramp) and duration T_c. In this case, the frequency can be defined as:

$$f(t) = f + \frac{B}{T_c}t. \tag{7}$$

Under the optimal transmission conditions that the transmitted signal is interference and noise free, the target vehicle return signal is affected by the delay and the Doppler shift, so the target return signal can be presented as follows:

$$R_{up}(t) = \cos\left[2\pi\left(f + \frac{1}{2}\frac{B}{T_c}\left(t - \tau - \frac{2V}{c}t\right)\right)\left(t - \tau - \frac{2V}{c}t\right)\right], \tag{8}$$

where τ is the delay (round trip time to the target vehicle), and it is given by

$$\tau = \frac{2R}{c}, \tag{9}$$

where R is the target vehicle range; V is the relative velocity; and c is the light velocity.

The simulation is made by using an ultra wide band (UWB) FMCW radar sensor where the bandwidth equals to 600 MHz and central frequency 24 GHz. The modulation time is 0.0625 sec which means that the up-sweep time is 0.03125 sec. The probability of false alarm P_{FA} is set to be constant and equals to 10^{-3}, and it is also used to define the detection threshold that can be presented in the following form [7]:

$$K_g = \sigma_n\sqrt{-\ln P_{FA}}. \tag{10}$$

In order to find out the practical performance of the proposed target vehicle detection technique, the practical probability of detection is defined after number of observations equal to M. This simulation method allows us to enhance the accuracy of decision about the presence of the target vehicle, and helps to obtain a practical simulated detection performance based on the relation between the signal to noise ratio (SNR) and the probability of detection P_D. Fig. 3 shows the basic generalized detector output signals when the model signal generator (MSG) is off.

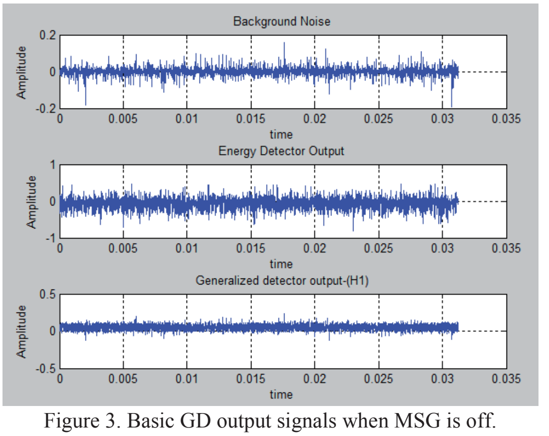

Figure 3. Basic GD output signals when MSG is off.

The simulation value of P_D is defined as the ratio between the number of frequency components that exceed the threshold K to the total number of observations M:

$$P_D = \frac{K}{M}. \tag{11}$$

Detection performance comparison is made between the GD and cell average constant false alarm rate (CA-CFAR) detector which is known to have the best detection performance among all CFAR techniques [8]. The initial conditions for both detectors are same and the number of observations M=100 (Fig. 4).

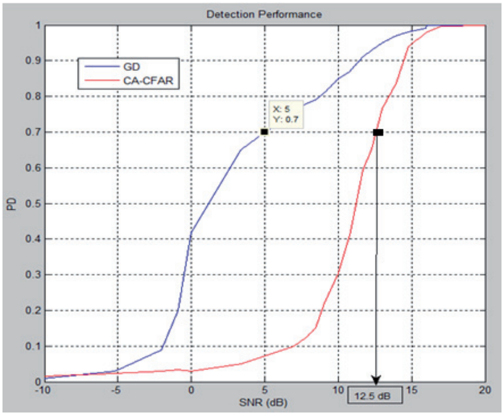

Figure 4. CA-CFAR and GD performance comparison.

From Fig. 4, we can see for example, in the case of probability of detection P_D equals to 0.7, the required SNR for CA-CFAR detector is approximately 12.5 dB, but for GD the required SNR equals to 5 dB. Thus, the GD performance under low SNR conditions is better than the performance of CA-CFAR detector with the same initial conditions.

4. Conclusion

One of disadvantages of FMCW radar sensor system is the sensitivity toward noise problem, especially for MRR and SRR applications, which is a characteristic of CVD system. The popular signal processing and detection techniques for the target return signal such as CFAR has low performance at the high level noise and interference in comparison with proposed GA. The generalized approach (GA) demonstrates the better detection performance at the same conditions and promises the higher probability of detection. The GA to signal processing in noise can be applied to improve the range resolution, phase adjustment, the estimation of direction of arrival (DOA) and other aspects that are a future work and vision for this research.

Acknowledgments

This research was supported by SL Corporation and Industry-Academic Cooperation Foundation, KNU research project (Grant No.20101459000).

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