Autonomous radar interference detection and mitigation using neural network and signal decomposition

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ABSTRACT

Autonomous radar interference is a challenging problem in autonomous vehicle systems. Interference signals can decrease the signal-to-interference-noise ratio (SINR), and this condition decreases the performance detection of autonomous radar. This paper exploits a neural network (NN) and signal decomposition to detect and mitigate radar interference in autonomous vehicle applications. A NN with four inputs, one hidden layer, and one output is trained with various signal-to-noise ratio (SNR), interference radar bandwidth, and sweep time of autonomous radar. Four inputs of NN represent SNR, mean, total harmonic distortion (THD), and root means square (RMS) of the received radar signal. Variational mode decomposition (VMD) and zeroing based on a constant false alarm rate (CFAR-Z) are used to mitigate radar interference. VMD algorithm is applied to decompose interference signals into multi-frequency sub-band. As a result, the proposed NN can detect radar interference, and NN-VMD-CFAR-Z can increase SINR up to 2 dB higher than the NN-CFAR-Z algorithm.

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1. INTRODUCTION

The research and development in intelligence transport systems (ITS) are still growing up until now, such as research in autonomous vehicles, vehicles to vehicles (V2V), and vehicle to infrastructure (V2X) [1]–[5]. An autonomous vehicle needs more sensors, such as ultrasound, light detection and ranging (LiDAR), camera, and radar (radio detection and ranging). mmWave radar sensor with frequency-modulated continuous wave (FMCW) is commonly used in autonomous vehicles [6]. FMCW radar promises high resolution in short-range detection, needs less power, and better performance in various conditions such as foggy, rainy, and dark environments than others.

However, implementing FMCW in dense autonomous vehicle cause serious signal interference. Radar signal interference can decrease radar target detection since radar signal interference decreases signal-to-interference-noise ratio (SINR), resulting in false detection or miss detection [7]. An adaptive noise canceller (ANC) with a conventional threshold has been introduced to mitigate radar interference [8]. The performance mitigation depends on the threshold value. If the signal power of the interference signal is lower than the desired threshold, the interference signal is not filtered. Wavelet denoising and constant false alarm rate (CFAR) are also explored to mitigate radar interference [9]–[11]. Both methods can suppress interference signals with high complexity processing and need adaptive threshold. Signal decomposition was also introduced to mitigate radar interference [12]–[16]. Signal decomposition extracts interference signals into several sub-band signals in the frequency spectrum. Frequency hopping mitigates radar interference [17] by changing frequency with a specific pattern based on time. This method needs a complex receiver to synchronise the transmitted and received signal.

In recent years, artificial intelligence (AI) has been widely used in many applications, with no exception in autonomous vehicles. Neural or deep neural networks (DNN) have also been explored to mitigate radar signal interference. DNN applied in radar doppler matrix (RDM) to reduce signal interference [18]–[21]. RDM needs more resources and processing time. It is not suitable to be implemented in low-resource modules. Other methods to mitigate interference in synchronous and asynchronous interference are also explored in [22], [23]. Meanwhile, an adaptive threshold was also introduced, but still a high-complexity process [24], [25].

This paper proposed a simple neural network (NN) to detect radar signal interference based on feature signal interference such as mean, root mean square (RMS), signal-to-noise ratio (SNR), and total harmonic distortion (THD). Variational mode decomposition (VMD) is introduced to extract signal interference to multiple frequency sub-bands. The next step is the zeroing process based on CFAR implemented on each sub-band frequency of VMD output to suppress interference signal.

2. METHOD

We proposed a method to increase SINR consisting of detection and mitigation. A NN is used to detect signal interference and joined VMD with constant false alarm rate-zero (CFAR-Z) algorithm to combat radar interference signal. The proposed method is shown in Figure 1. Received signals are digitised using an analog-to-digital converter (ADC) as raw signals. Raw signals will be extracted to get mean, RMS, SNR, and THD parameters as NN inputs. VMD-CFAR-Z algorithms process raw signals if contaminated with interference, while fast fourier transform (FFT) will process non-interference signals to get the radar range profile.

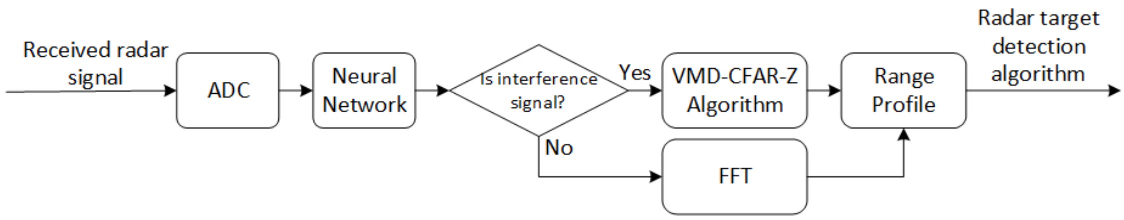

Figure 1. Radar interference detection and mitigation method

2.1. mmWave frequency modulated continuous wave

mmWave frequency modulated continuous wave (FCMW) radar is used in autonomous vehicles to detect targets along the road in short and long-range modes. The advantages of using mmWave FMCW radar are high-resolution detection and less power to transmit a chirp signal. The transmitted signal $y(t)$ of FMCW is expressed in (1).

$$y(t) = e^{j2\pi(f_o t + Kt^2/2)}, 0 < t < T \quad (1)$$

Where f_o, K, and T represent starting frequency, sweep slope, and time duration, respectively. Meanwhile, a received signal consists of a reflected, transmitted signal by target and noise. If any radars in confront position each other, the received signal is added by the interference signal $s_i(t)$. A beat signal after the mixer and low pass filter in receive part of FMCW radar as formulated in (2).

$$r_b(t) = s_b(t) + s_i(t) + n(t) \quad (2)$$

where $r_b(t)$, $s_b(t)$, and $n(t)$ represents beat signal, echo signal from targets, and noise from the environment, respectively.

2.2. Neural network

A NN consists of an input, hidden, and output layer. This research's input layer consists of four inputs from the mean, RMS, SNR, and THD of the received signal, while a hidden layer consists of ten neutrons and one output layer, as shown in Figure 2. Levenberg-Marquardt backpropagation and mean squared error (MSE) are used to train the proposed NN.

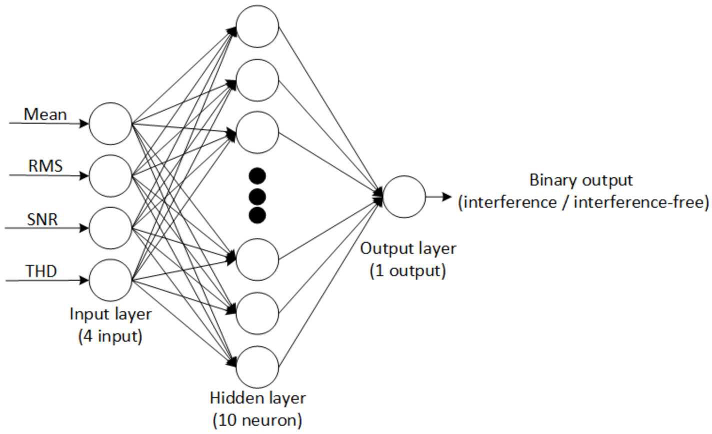

Figure 2. Proposed NN

2.3. Signal decomposition

VMD is a signal decomposition from $x(t)$ signal to N narrowband intrinsic signal (NIMFs) as expressed in (3):

$$x(t) = \sum_{k=1}^{K} u_k(t) \tag{3}$$

where $u_k(t)$ is the frequency and amplitude-modulated signals. Optimation of the VMD algorithm is discussed in [26].

2.4. Constant false alarm rate–zero

CFAR-Z has been introduced in [11], where it is proposed to mitigate radar interference with low complexity and reliability to implement in the actual board. CFAR-Z outperforms ANC and wavelet denoising. CFAR-Z algorithm is based on cell-averaging (CA)-CFAR to detect the peak signal of the spectrum signal in the frequency domain. The detected signals are replaced with zero to remove interference in the received signal.

3. RESULTS AND DISCUSSION

3.1. System model

Autonomous vehicle radar interference occurs when two vehicles or more co-front each other on the road, as modelled in Figure 3. Radar interference is categorised into two models: interference with different radar parameters, such as difference in sweep time, and interference caused by the same radar parameter between the aggressor and victim car. We simulate one victim and three aggressor radars with varying parameters. Three aggressors were placed in different locations relative to the victim's radar. Generally, all victim and aggressor radar use mmWave radar with a frequency of 77 GHz, as tabulated in Table 1.

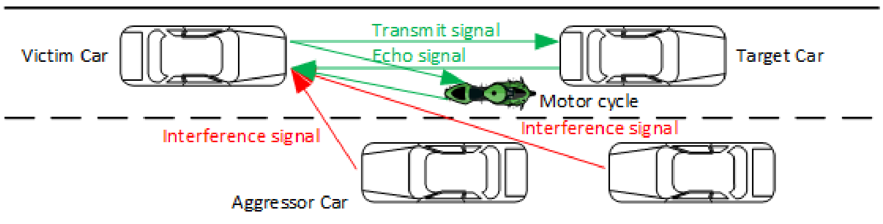

Figure 3. Radar interference scenario

Table 1. System model parameters

Parameters	Victim radar	Aggressor radar
Center frequency (GHz)	77	77
Max range detection (m)	250	250
Sample rate (MHz)	40	40
Bandwidth (MHz)	600	300,900,300
Sweep duration (µs)	100	100, 100, 100
Sweep slope (MHz/ µs)	6	3, 9, 3
Interference delay time (µs)	-	5, 10, 20

This research simulates radar interference caused by three aggregator radars with different bandwidths, as shown in Table 1. A victim radar also detects targets from four targets with different location as follow: 5 m, 10 m, 15 m, and 20 m in front of a victim radar. The generated signal in the time domain for non-interference and interference conditions under additive white Gaussian noise (AWGN) -10 dB is shown in Figure 4.

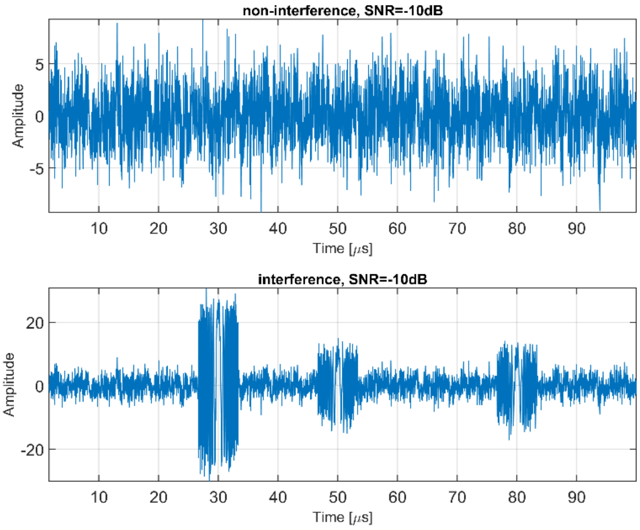

Figure 4. Interference-free and interference radar beat signals in the time domain

The FFT is applied to get the range profile of the received signal, as shown in Figure 5. Some target signals in a range of 10 m, 15 m, and 20 m are uncleared enough to detect as a target radar caused by interference signal. The noise floor signal increases from -25 dB to -15 dB, which means the SINR received signal decreased.

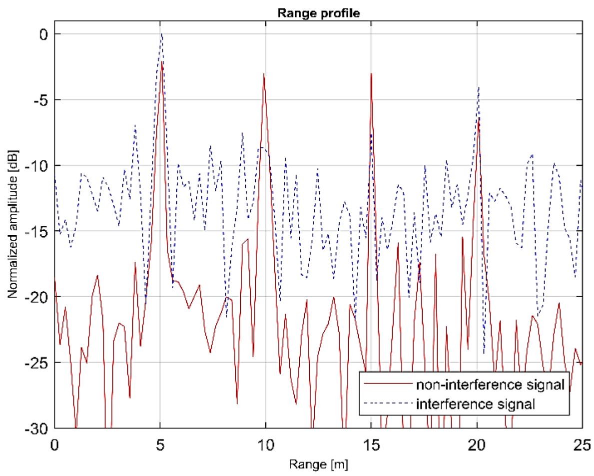

Figure 5. Range profile for non-interference and interference signal after FFT processing

3.2. Neural network

We designed a simple NN with a compact architecture and easily implemented in the actual board, as shown in Figure 2. The NN input is the received signal features such as SNR, THD, mean, and RMS. The total data train is 100,000, consisting of interference and non-interference signals, where each category has 50,000 data. The NN is trained with three aggressor radar with varying time slope and different interference delay time under varying SNR from 1 to 5 dB. Levenberg–Marquardt algorithm and MSE are used along the training NN. The performance of the NN is shown in Figure 6.

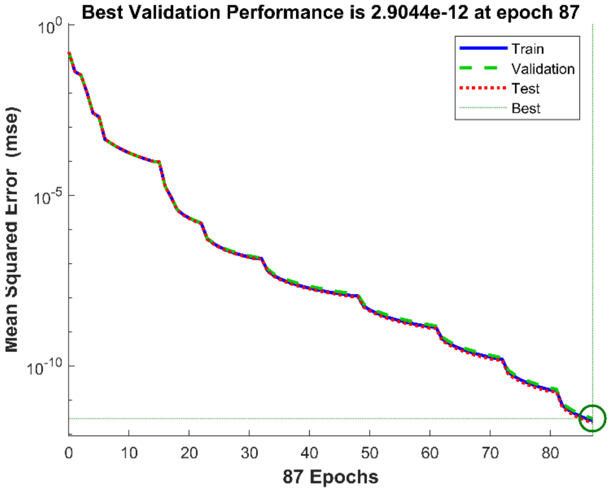

Figure 6. NN performance

3.3. Interference mitigation

This paper proposes the mitigation of interference radar by combining signal decomposition with a zeroing process based on a CFAR-Z. VMD with $NumIMF = 9$ is used to extract the detected interference signal into nine sub-band signals. CFAR-Z processing is implemented for $NumIMF = 4$ to $NumIMF = 9$, while others $NumIMF$ is considered as interference and noise only. After training NN, we test our proposed method with parameters as listed in Table 1 under AWGN noise -10 dB. The result of interference mitigation processing is shown in Figure 7.

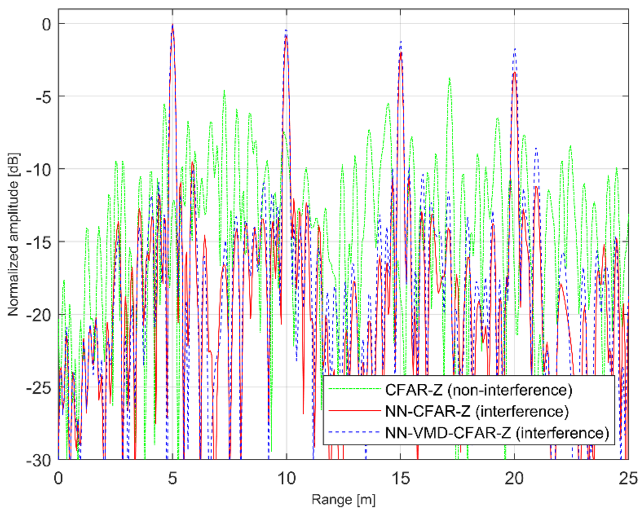

Figure 7. Mitigation performance for various methods

Figure 7 shows that the CFAR-Z algorithm underperforms to mitigate targets under the non-interference received signal. A simple NN is proposed to detect whether or not the received radar signal is contaminated with other signal radar. The proposed algorithm, NN-VMD-CFAR-Z, outperforms another method with increased SINR up to 2 dB than the NN-CFAR-Z algorithm. The average increased SINR by the NN-VMD-CFAR-Z algorithm under various AWGN noises is tabulated in Table 2. All simulation was processed on a computer with 11th Gen Intel(R) Core (TM) i7-1165G7 @ 2.80 GHz and 8 GB installed RAM. The processing time is analysed to show the saving time process between interfered and non-interfered waveforms, and the result is shown in Table 3. From Table 3, the proposed NN can save significant processing time of up to 1.65 seconds and avoid underperforming CFAR-Z in the non-interfered waveform.

Table 2. Increased SINR by NN-VMD-CFAR-Z algorithm

Parameters	AWGN=-15dB	AWGN=-10dB	AWGN=-5dB	AWGN=0dB
SINR-based (dB)	-18.85	-17.42	-16.78	-16.65
SINR-NN-CFAR-Z (dB)	8.00	11.30	15.34	18.6
SINR-NN-VMD-CFAR-Z (dB)	10.60	14.27	18.45	21.19

Table 3. Processing time

Parameters	Time (s)
Pre-processing data	0.004810
NN-CFAR-Z	0.105028
NN-VMD-CFAR-Z	1.652097
FFT (non-interference)	0.000061

4. CONCLUSION

Radar interference detection and mitigation has been simulated and evaluated under various noise and interference signal condition. A simple and compact designed NN performs well in detecting interference signals. The proposed method, NN-VMD-CFAR-Z, outperforms with increases SINR up to 2 dB on average higher than NN-CFAR-Z algorithm.

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