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Echo signal extraction method of laser radar based on improved singular value decomposition and wavelet threshold denoising

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ABSTRACT

Aiming at the problem of the weak echo signal for laser radar, the probability detection model of the laser radar is set up, and the influence of different signal to noise ratio and the threshold noise ratio is analyzed. The denoised process can effectively improve the detection probability. Therefore, two-level denoising framework with singular value decomposition and adaptive wavelet denoising is proposed. The improved method of selecting singular value based on curvature spectrum is proposed. On this basis, the selection criterion of decomposition level of adaptive wavelet denoising is put forward, and the optimal threshold is obtained by using continuous derivable threshold function and gradient descent. The joint denoising performance of singular value decomposition and adaptive wavelet denoising under Gaussian white noise is simulated and analyzed. The echo signal denosing experiments show that the amplitude of the peak noise is reduced by 10 times on the basis of the effective retention of the echo signal.

1. Introduction

Laser radar is widely used in robot navigation [1,2], 3D imaging [3], space detection [4], target recognition and tracking etc. [5,6]. In detection process of pulsed laser radar, the amplitude of echo signal varies extremely by the size and scattering characteristics of targets. Whilst the signal-to-noise ratio (SNR) of echo signal is at a lower level, the target could not be detected effectively with leading edge detection [7]. Moreover, electromagnetic interference signal caused by the high pulse current of laser emission system will be coupled to the echo signal. In order to guarantee the detection performance, the echo signal buried in noise should be extracted with denoising algorithm.

There are several signal denoising methods such as empirical mode decomposition, singular value decomposition (SVD) and wavelet denoising. There is less phase shift and no delay for SVD method, which has been used in the fields of image coding [8], watermark [9], and medicine [10]. It is difficult to determine the number of singular value reconstruction using traditional methods such as singular value curvature spectrum [11], singular value difference spectrum [12] and singular entropy increment [13]. The peak point is as the dividing point between the signal and noise for curvature spectrum and difference spectrum. However, the original signal is mixed in the low energy singular value in the situation of low SNR in actual. The part signal will be lost only using boundary point. Meanwhile, there are fewer differences between singular value curvature spectrum and singular entropy increment. Furthermore, there is no obvious feature that can be used to determine the number of effective singular values for singular entropy increment. Dai proposed an improved singular value denoising order selection method [14], which was used to retain more original signals at low SNR. However, a better waveform is not obtained for echo signal. Thus, SNR must be increased by other methods. Wavelet threshold denoising is a commonly used method, which has been applied in many fields such as laser radar, gear fault diagnosis and image edge extraction [15–17]. It is significant to choice wavelet threshold function, decomposition level and given wavelet base. In the aspect of wavelet threshold function, the power function and semi-soft function were employed to improve the performance of wavelet denoising [18,19]. In addition, Wang constructed a sin threshold function [20] for imaging denoising and acquired outstanding image details. Furthermore, Li took advantage of power function and exponential function to modify the threshold function and analyzed the vibration signal of vehicle platform [21]. Compared with the traditional soft and hard threshold function, the above functions overcome disadvantages of the continuity problem. Nevertheless, multiple variables, included in function, need to be determined to obtain best denoising effect. Therefore, Nasri searched for the optimal threshold through supervision and unsupervised learning methods [16]. The threshold was searched by improved particle swarm optimization algorithm [22]. Han used

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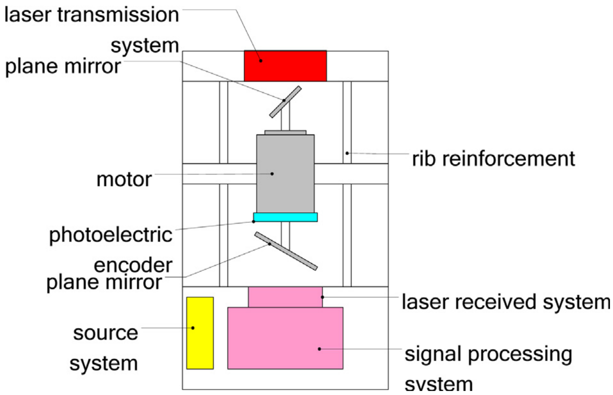

Fig. 1. Schematic diagram of the structure of laser radar system.

genetic algorithm to search the best threshold utilizing intelligent optimization algorithm under the lifting wavelet framework [23]. But time cost will increase accordingly. Additional, the above researches obtained wavelet decomposition level based on empirical analysis and did not give the adaptive selection criteria.

In this paper, two-level denoising framework based on singular value decomposition and adaptive wavelet denoising is proposed. In Section 2, the influences of different SNR and threshold-noise ratio (TNR) on target detection probability are deduced and analyzed, and the importance of denoising preprocessing is expounded. In Section 3, modified singular value selection method of curvature spectrum is put forward, and the flow of SVD denoising algorithm is given. In Section 4, the guided wavelet function is further used to reduce the noise and extract the characteristics of the laser echo signal. Finally, the effectiveness of echo signal denoising is verified by simulations and experiments compared with the other algorithms.

2. Detection probability model

The schematic diagram of laser radar system is shown in Fig. 1. The laser transmission system consists of drive circuit, laser diode and collimating lens is fixed at the top of the mechanical structure. The plane mirror is connected to both ends of the bidirectional motor through thread. The scattered light reflected by target could enter the laser received system, which is composed of amplified circuit, the photo detector and the focusing lens. The signal processing system that is made up of threshold detection circuit, time discrimination circuit and programmable logic gate array calculate the distance between laser radar and target. The power system is installed on the side of the signal processing system to supply energy to other subsystems. The rotation angle is obtained by photoelectric encoder.

The received signal of laser radar is

$$V_{sn}(t) = V_s(t) + V_n(t) \tag{1}$$

where $V_s(t)$ is ideal received signal, and $V_n(t)$ is noise signal.

The noise of laser received system can generally be described by Gaussian distribution. Therefore, if received system noises are zero mean Gaussian white noises, and the probability density function of noise could be expressed as:

$$p(V_n(t)) = \frac{1}{\sqrt{2\pi}\bar{V}_n}\exp\left(-\frac{V_n^2(t)}{2\bar{V}_n^2}\right) \tag{2}$$

where $\bar{V}_n$ is equivalent root mean square (RMS) voltage of noise.

The false alarm rate is

$$P_F = \int_{V_{th}}^{\infty} p(V_n(t))dV_n(t) = \frac{1}{2} - \frac{1}{2}\mathrm{erf}\left(\frac{V_{th}}{\sqrt{2}\bar{V}_n}\right), \tag{3}$$

where erf() is error function.

Ideal received signal is

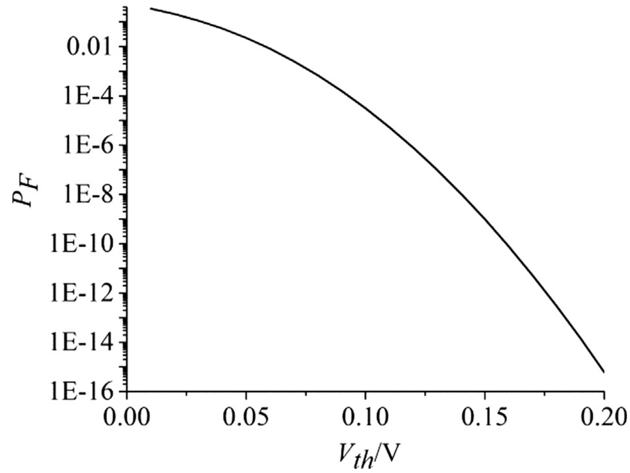

Fig. 2. False alarm rates under different threshold voltages.

$$V_s(t) = V_P\exp\left(-\frac{(t-t_e)^2}{2\sigma^2}\right) \tag{4}$$

where V_P is peak voltage, σ is pulse width, and t_e is peak time.

The detection probability is

$$P_D = \int_{V_{th}}^{\infty} p(V_{sn}(t))dV_{sn}(t) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{V_P\exp\left(-\frac{(t-t_e)^2}{2\sigma^2}\right) - V_{th}}{\sqrt{2}\bar{V}_n}\right)$$
$$= \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{1}{\sqrt{2}}\left(\mathrm{PSNR}\cdot\exp\left(-\frac{(t-t_e)^2}{2\sigma^2}\right) - \mathrm{TNR}\right)\right) \tag{5}$$

where PSNR is defined as the ratio of peak voltage to $\bar{V}_n$, and TNR is defined as the ratio of threshold voltage to $\bar{V}_n$.

Assume that $\bar{V}_n$ is 0.025 V. The false alarm rates at different threshold voltages are shown in Fig. 2. The false alarm rate is less than 10^{-4} when TNR is 4. Therefore, the false alarm rate is less than 0.01% when the threshold is 0.1 V.

Assume that $V_{th} = 0.1$ V, $\bar{V}_n = 0.025$ V, $\sigma = 20$ ns, $t_e = 3.33 \times 10^{-7}$ s. The detection probability distributions are shown in Fig. 3. It can be seen from Fig. 3 that the pulse signal is time-varying. With the increase of time, the detection probability increases first and then decreases. In addition, with the increase of echo peak voltage, the detection probability increases. When the echo signal reaches the peak value, the error function obtains the extreme value, and the detection probability also obtains the maximum value. Therefore, the maximum detection probability of peak time is defined as the effective detection probability in

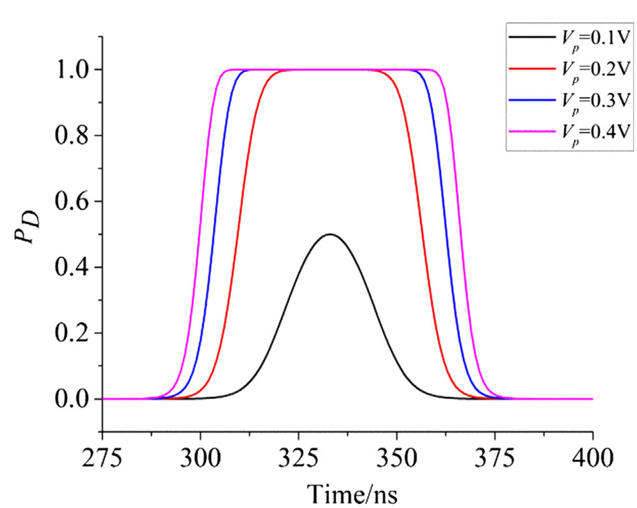

Fig. 3. Detection probability distribution at different time.