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A method for automatic preprocessing of laser echo signals based on FPGA

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Abstract

When exploring various unknown environments, laser detection technology can effectively reveal depth information and unknown terrain of complex scenes. However, due to the susceptibility of the laser echo signal received by the detector to noise interference and the limitation of the oscilloscope sampling rate when reproducing on the oscilloscope, this may lead to a decrease in the accuracy of the echo signal. Therefore, choosing an appropriate preprocessing method to optimize the echo signal is crucial for subsequent waveform analysis. This study adopts an advanced signal processing strategy, which converts the echo signal into the frequency domain by performing Fast Fourier Transform (FFT), and then automatically identifies and selects key frequency bands using precise algorithms to determine the specific cutoff frequency. Subsequently, based on the key cutoff frequency parameters and preset other parameters, the coefficients of the FIR filter were calculated in the FPGA and applied to the FIR filter module for signal filtering, achieving real-time signal processing. This method significantly improves the accuracy and efficiency of signal processing, providing valuable reference for practical application scenarios.

Keywords

Laser Detection; Echo Signals; FFT; Algorithms; FIR.

1. Introduction

In recent years, the exploration of unknown terrain and complex environments has increasingly relied on advanced technological means, among which laser detection technology has played a key role[1] .This technology can penetrate unknown curtains and depict invisible terrain contours, providing enormous potential for scientific research, environmental monitoring, and even architecture and archaeology. However, the journey from raw laser echo signals to feasible insights is full of challenges. The integrity of these signals is often compromised due to environmental noise and inherent limitations of measuring instruments such as oscilloscopes.

Given these challenges, this article delves into the key stages of signal preprocessing, which serve as a bridge between raw data acquisition and detailed terrain analysis[2]. This study focuses on an advanced signal processing strategy that utilizes Fast Fourier Transform (FFT) to transition from time-domain analysis to frequency-domain analysis[3]. By intelligently identifying key frequency bands and calculating accurate cutoff frequencies, this method lays the foundation for the application of Finite Impulse Response (FIR)[4] filters within field programmable gate arrays (FPGAs). This integration not only simplifies the preprocessing workflow[5], but also improves the accuracy and efficiency of the laser detection system. The following discussion provides a comprehensive overview of this innovative signal processing technology, emphasizing its importance and practicality in improving the accuracy of laser-based exploration[6].

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2. Research Contents

2.1. Conventional waveform preprocessing methods

In the field of digital signal processing, the diversity of preprocessing techniques provides a wealth of options for accurate analysis and application of data. Among these, Finite Impulse Response (FIR) filters serve as a significant preprocessing tool. By processing signals in the time domain, FIR filters exhibit their unique advantages. The working principle of FIR filters is based on the linear convolution of the input signal with a series of predefined filter coefficients (also referred to as taps or weights), effectively removing noise from the signal waveform. These coefficients are critical to the filter's performance.

The precise generation of these coefficients is the core of FIR filtering. Currently, this process typically relies on professional tools like MATLAB's built-in Filter Design and Analysis Tool (fdatool), enabling users to set required parameters and generate the filter coefficients. The filter's performance is influenced by several parameters, such as the cutoff frequency, sampling rate, β parameter, and the filter's order. While the β parameter, sampling rate, and filter's order are usually predetermined, the selection of the cutoff frequency is based on spectral analysis of the signal, a process too complex to be fully automated within an FPGA.

Therefore, when preprocessing an unknown signal with an FIR filter, it is essential first to perform spectral analysis of the signal in software such as MATLAB, to identify the noise frequency range. Subsequent to this analysis, and based on the specific application requirements, the cutoff frequency, sampling rate, β parameter, and filter order are determined. Finally, tools like fdatool are utilized to generate and output the filter coefficients.

The implementation of an FIR filter can be divided into three main stages: data delay, where the input signal is progressively delayed along the time axis; data multiplication, where each delayed signal is multiplied by the corresponding filter coefficient; and data accumulation, where these products are summed to form the final filtered output. This process ensures that the desired frequency components of the signal are preserved while the unwanted frequency components are effectively attenuated or removed.References, see Fig.1.

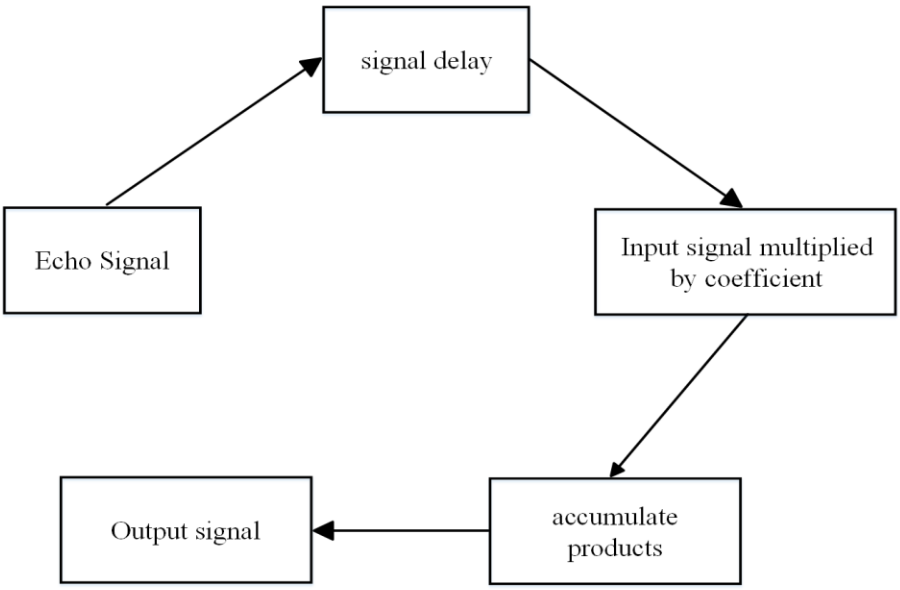

Fig.1 FIR flowchart

2.2. Experimental Results and Analysis

Confronted with the limitations inherent in traditional waveform preprocessing methods for the automatic identification and selection of cutoff frequency parameters, this study introduces a novel strategy. This approach employs real-time Fast Fourier Transform (FFT) to process echo signals and utilizes a counter for point-by-point tallying of the FFT results, thereby pinpointing peak frequencies across different bands with precision within the frequency domain (calculated as the product of the clock frequency and the counter value, divided by the FFT's transformation length). By delving into the FFT spectrum, we have delineated key parameters to traverse the real part of the FFT results and to accurately extract all points of maximum amplitude. Given that the real part of FFT exhibits sinusoidal characteristics, the maximum amplitude is invariably located at these points of maximum. By introducing an additional parameter for peak tracking, this method ensures the stable capture of the maximal values within the real part of FFT, designating a threshold below which a value is identified as the demarcation between signal and noise, clearly marked by an activated flag signal.

Moreover, the study meticulously crafts a mechanism for determining the cutoff frequency, accomplished by computing the counter value corresponding to the demarcated signal-noise threshold point, multiplied by the clock frequency and divided by the FFT's transformation length. Once the cutoff frequency has been ascertained, we harness a floating-point arithmetic IP core to carry out precise calculations for the coefficients required by the FIR filter. Preceding the FFT analysis that determines Fc, the parameters β, Fs (sampling rate), and the filter order can be pre-set. Owing to the symmetric nature of FIR filter coefficients, for odd-ordered filters, it is only necessary to compute the coefficients up to the midpoint; for even-ordered filters, the latter half of the coefficients mirrors the first half. These computed coefficients are then conveyed to the subsequent FIR filtering module, effectuating the automatic preprocessing of the echo signal. This methodology not only enhances the optimization of the preprocessing workflow but also significantly bolsters the efficiency and accuracy of data processing. References, see Fig.2.

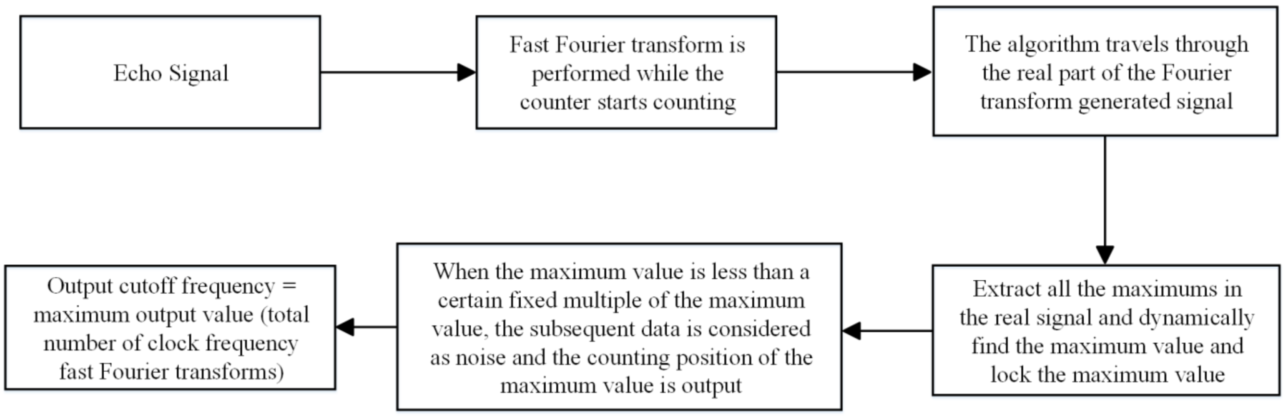

Fig. 2 Algorithm execution flowchart

2.3. Innovation in signal preprocessing methods

In this study, we employed a laser emitter to target the water surface and captured the real data reflected back through a detector for in-depth analysis. The experimental data was transmitted to an FPGA, facilitating a comprehensive evaluation of the results based on a comparison of the signal-to-noise ratio (SNR) before and after preprocessing: initially, the SNR of the raw data was calculated to serve as a baseline; subsequently, the SNR of the preprocessed data was recalculated to act as a key standard for performance assessment. Employing this approach, we conducted detailed comparative analyses on eight sets of data. This comparative process not only allowed us to directly observe how preprocessing effectively improves the SNR, but also provided valuable empirical evidence for further optimizing our signal processing strategies.

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Below, we present the actual waveform data, along with the visual representation in Vivado software both before and after preprocessing, as well as a comparison of the signal-to-noise ratio (SNR) across eight data sets. It is observable from the graphical representations that the peaks of the waveforms become significantly clearer post-preprocessing, which substantially enhances the performance of laser lidar ranging. Similarly, the comparison of SNR across the eight sets clearly demonstrates a notable improvement in the results following preprocessing. This evidence suggests that the employed method significantly boosts the preprocessing efficiency, achieving automation while simultaneously enhancing the signal's SNR.References, see Fig.3.4. and Table 1.

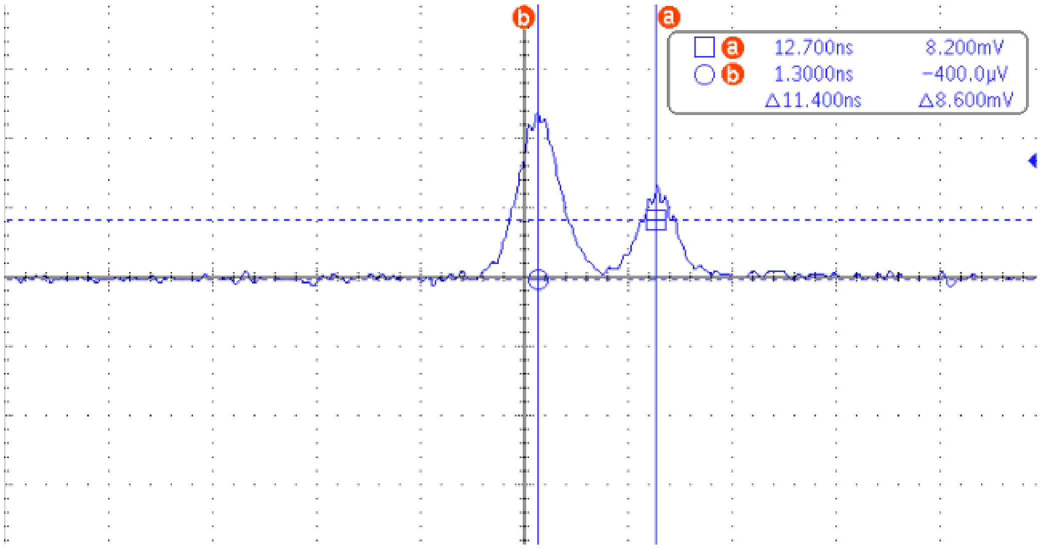

Fig. 3 The measured data displayed by the oscilloscope

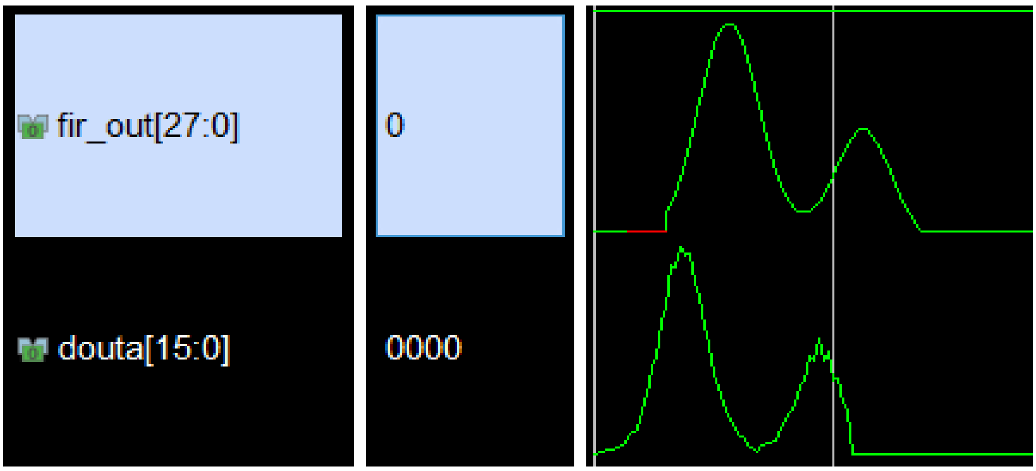

Fig.4 Comparison before and after waveform preprocessing

Table 1 Comparison of signal-to-noise ratio before and after waveform preprocessing

Before	16.73db	17.36db	17.98db	18.21db	14.74db	16.50db	18.04db
After	53.38db	59.72db	61.07db	57.53db	50.54db	55.79db	60.75db

3. Conclusion

This study introduces a method for automatic signal preprocessing, integrating a Fast Fourier Transform (FFT) module with a set of algorithms for automatically finding key parameters. This approach optimizes the data preprocessing workflow, which was previously incapable of real-time processing, into a process that can be executed in real-time. By employing an improved algorithm, the method not only achieves automation of the entire processing procedure but also significantly enhances the signal-to-noise ratio of the raw data and the precision of peak locations. This approach provides practical reference value for applications such as laser lidar ranging, demonstrating the potential of technological innovation to improve data processing efficiency and accuracy in practical applications.

References

[1] Huan, Li, and Yu Hongying. "Design of high performance lidar ranging system based on FPGA", Electronic Measurement Technology 44.20 (2021): 6-10.

[2] ZHANG H, ZHANG T, WAN S, JIANG Y, SU X, et al. Audio signal pre-processing system based on FPGA[J], Electronic Design Engineering, 2023, 31(14)

[3] Hans K, Tobias M, Mario G, Kent P, Oscar G, et al. A 1 Million-Point FFT on a Single FPGA[J], IEEE Transactions on Circuits and Systems I: Regular Papers, 2019, 66(10): 3863-3873.

[4] Du, Yong. "A new method of filter coefficient quantization", Application of Electronic Technique 45.4 (2019): 52-54,59.

[5] Cong L, Xin X, Rui W, Ye S, et al. Design and implementation of digital signal processing module based on FPGA[J], Computer Engineering and Design, 2020, 41(6): 1586-1591.

[6] Hongbin M, Jianhua S, Shiguang P, Yuan L, Yan H, et al. Research on the low-cost pulse laser ranging system[J], Information Technology and Network Security, 2020, 39(9): 74-78.