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Utilizing Fast Fourier Transform in the processing of biomedical signals: An analytical approach

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Abstract. Fast Fourier Transform (FFT) is an indispensable tool in biomedical engineering, which optimizes the computational process of the traditional Discrete Fourier Transform (DFT) and effectively reduces the computational complexity. This paper first introduces the basic principle of FFT and its importance in biomedical signal processing. It focuses on the application of FFT in the analysis of electrocardiogram (ECG) and electroencephalogram (EEG) signals, such as the diagnosis of arrhythmia and the analysis of sleep quality, as well as the importance of FFT in removing biomedical signal noise. In addition, the paper explores FFT discussing its challenges and future directions in biomedical engineering, including the development of new algorithms and integration with machine learning techniques. Finally, the article summarizes the applications of FFTs in biomedical engineering and their importance. It emphasizes the need for continued research and development of FFTs and their related techniques in the biomedical field.

Keywords: FFT, ECG, EEG, Biomedical signal processing.

1. Introduction

The Fast Fourier Transform (FFT) is an efficient algorithm for computing the Discrete Fourier Transform (DFT) and its inverse, which has been widely used in various fields since the middle of the 20th century, especially in biomedical engineering. The core advantage of the FFT lies in its low computational complexity (O(N log N)), which makes it ideal for analyzing a variety of biomedical signals. In biomedical engineering, FFTs are used to analyze electrocardiograms (ECGs), electroencephalograms (EEGs), and other biomedical signals for the diagnosis and study of disorders such as arrhythmias, myocardial ischemia, and epilepsy, as well as for a variety of applications such as sleep quality analysis. This paper delves into the mathematical foundations of FFT, how it optimizes the computational process of DFT and its wide range of applications in biomedical engineering. By analyzing in-depth cases of its application in ECG and EEG signal processing, this paper reveals the importance of FFT in modern medical diagnosis and disease research. Meanwhile, this paper also discusses the challenges faced by FFT in biomedical engineering and the possible future directions, such as the development of new algorithms and the combination with machine learning techniques, to look forward to the future applications of FFT in biomedical fields.

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2. Theoretical background of FFT

2.1. Discrete Fourier transform (DFT)

Mathematical principle: Discrete Fourier Transform is the discrete form of continuous Fourier transform. It converts a signal discrete in the time domain into a signal in the frequency domain. For a complex sequence x[n] of length N(n=0,1,...,N-1), its DFT is defined as X[k]=∑(n=0 to N-1) x[n]-e^(-j2πkn/N). Where X[k] denotes a complex sequence in the frequency domain and k represents the frequency index (k=0,1,...,N-1). This transform is reversible, i.e., it can be transformed back to the original time-domain signal by an inverse DFT (IDFT). The DFT allows us to analyze the components of a signal at different frequencies, which is crucial in areas such as spectrum analysis, filter design, and signal compression.

2.2. Fast Fourier transform (FFT)

Optimization principle: FFT is a fast algorithmic implementation of DFT. For a sequence of length N, direct computation of the DFT requires a time complexity of O(N^2), while the FFT reduces this complexity to O(N log N).

Computational Complexity and Advantage: Since the FFT reduces the time complexity to O(N log N), it significantly improves the efficiency when processing large-scale data. This is critical for applications such as real-time signal processing and spectral analysis of large amounts of data.

2.3. Basic signal processing concepts

The frequency domain is obtained by Fourier transform and describes the intensity and phase of a signal at each frequency. It provides us with a way to understand and analyze signals from another perspective.

The sampling theorem is the basis of digital signal processing. It states that in order to recover a discrete signal from a continuous signal without distortion, the sampling frequency must be at least twice the highest frequency of the signal. This principle is important to avoid aliasing during digitization. These concepts and methods have a wide range of applications in many real-world applications, such as audio and video processing, communication systems, radar signal processing, and so on. By performing Fourier analysis on signals, we are able to better understand their properties and process and analyze them effectively. In addition to the mathematical field, FFT has a wide range of applications in biomedical collar engineering, through the development of new algorithms and integration with machine learning techniques to optimize the processing of signals, etc. [1].

3. Application of FFT in biomedical signal processing

In the field of biomedical engineering, the analysis and processing of biomedical signals occupy a central position. These signals, such as electrocardiograms (ECG), electroencephalograms (EEG), and electromyograms (EMG), contain crucial information for medical diagnosis and pathological research. The Fast Fourier Transform (FFT), as an efficient mathematical tool, plays an indispensable role in processing these signals.

The core advantage of the FFT algorithm lies in its efficiency. It decomposes complex signals into their frequency components, making the analysis and processing of signals simpler and more direct. This process not only enhances the useful information in the signals but also helps in identifying and filtering out noise, thereby improving the quality and interpretability of the signals.

3.1. Electrocardiogram (ECG)

Electrocardiogram (ECG or EKG) is a medical test that records the electrical activity of the heart. This test is performed by placing multiple electrodes on the patient to measure the electrical signals generated by the heart with each beat. ECG is an important tool for diagnosing and evaluating cardiac disorders and can provide valuable information about the function and structure of the heart.

Each contraction of the heart is triggered by electrical signals produced by specific cells of the heart. These electrical signals trigger the contraction of the heart muscle that pumps blood throughout the body. During an ECG, multiple electrodes are usually placed on the patient’s chest, arms, and legs. These

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electrodes capture the electrical activity generated by the heart. The ECG device records the electrical signals and converts them into a waveform graph that shows the details of the heart's electrical activity. ECG is a fundamental tool in heart health assessment, providing physicians with a visual way to observe and assess the electrophysiologic activity of the heart.

3.1.1. FFT for noise filtering. A common problem during ECG recording is interference at 50 or 60 Hz caused by power lines. This interference can significantly affect the quality of the signal, interfering with diagnosis. The FFT allows the identification and isolation of these frequency-specific interferences. By applying a band-stop filter, these frequencies can be effectively removed, thus clearing the power line noise from the ECG signal. Noise reduction using the FFT not only improves the quality of the ECG signal but also makes further signal analysis (e.g., rhythm analysis, detection of tachycardia) more accurate [2]. Short-Time Fourier Transform (STFT) can be used to calculate and analyze the energy distribution of ECG signals. It is essentially used to calculate the frequency intensity in the signal around time. Then features are extracted from the said energy distribution for use in classification algorithms. STFT is defined as follows:

$$\mathrm{STFT}(t, f) = \int x(t')\Gamma * e\hat{}(-j2\pi f t')dt' \tag{1}$$

This is the mathematical expression for the Short-Time Fourier Transform (STFT), which is a method used in signal processing to determine the local frequency components of time-varying signals. In this integral, x(t')$x(t')$ is the signal in the time domain, \Gamma$\Gamma$ is the window function used to determine the localized region of the signal, and e^{-j2\pi f t'}$e\text{-}j2\pi f t'$ is the core portion of the Fourier transform used to convert the signal to the frequency domain. The STFT is used to analyze the frequency components of a signal by sliding windows on the signal and applying a Fourier transform to analyze the frequency components of the signal at different points in time. Where x(t) is a finite-length window and x(t'-t) is the same window but centered at time t [2,3]. However, the STFT trades off between time resolution and frequency resolution, so its capabilities are limited by the accuracy of the frequency distribution. If the frequency domain resolution is increased, longer segments of ECG data are required; however, the longer the ECG data, the greater the variation in time domain frequency. This means that if we want high temporal resolution, we need shorter ECG data windows [3].

3.1.2. Specific steps. The classification algorithm utilizes a process that begins with importing an ECG signal, followed by signal preprocessing. After preprocessing, we perform the Short-Time Fourier Transform (STFT) as dictated by the equation. This leads to feature extraction, which involves three key features. The first feature is the Maximum Intensity Frequency or Peak Frequency, denoted as Fm. The second feature is the Normalized Energy in the peak frequency band, defined around Fm. The third feature encompasses the Normalized Energy of Fm harmonics. These three features are then further used in the classification algorithm [4,5].

3.2. Electroencephalography (ECG)

Electroencephalography (EEG) is a medical test that measures and records the electrical activity of the brain. It captures and records fluctuations in electrical signals in the brain by placing electrodes on the scalp. EEG is widely used to study brain function, as well as to diagnose and monitor various brain disorders.

During an EEG, multiple small electrodes are placed at specific locations on the scalp. These electrodes detect the weak electrical signals generated by neuronal activity in the brain. The electrical signals captured by the electrodes are converted into graphical or digital form to form a recording of brain waves. EEG is particularly important in the diagnosis of epilepsy because it captures abnormal waveforms of brain electrical activity, which is a classic sign of a seizure. By analyzing brain waves during sleep, EEG can also be used to diagnose sleep disorders. EEG is a very important tool in the field of neuroscience and clinical neurology, allowing researchers and physicians to monitor and analyze brain activity in real time.

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3.2.1. FFT applications for brain disease diagnosis. In the field of biomedical engineering, the Fast Fourier Transform (FFT) plays a crucial role in analyzing brain waves and detecting brain disorders, especially epilepsy. With FFT, researchers and physicians are able to extract key frequency features from electroencephalogram (EEG) signals to gain a deeper understanding of the electrophysiological activity of the brain and apply it to the diagnosis and treatment of a wide range of brain disorders. In particular, it has important applications in the diagnosis of epilepsy. During an epileptic seizure, the EEG shows abnormal electrical activity such as sudden high-frequency waves and synchronized brainwave patterns [6]. Using FFT, these abnormal signals can be detected quickly and accurately, thus helping doctors diagnose seizures in a timely manner and monitor the progression of the condition.

FFT transforms the time domain signal of an EEG into a frequency domain signal. This transformation allows analysts to more clearly observe the presence of different frequency components and their relative intensities. Different states of brain activity are characterized by different frequencies in the EEG signal. The FFT helps to identify specific states of brain activity by separating these different frequency components. Certain specific EEG patterns, such as α-waves, β-waves, δ-waves, etc., are associated with specific physiological or pathological states. FFT can help to recognize these patterns and thus provide a basis for the understanding of brain activity [3].

3.2.2. Integration with neural networks. Extracting discriminative and unique features is a key process in deploying a successful disease recognition system, and in this regard, a current state-of-the-art learning algorithm is a promising new feature extraction model based on Principal Component Analysis Networks (PCANet) that is capable of automatically learning features from EEG signals with both high accuracy and high generalizability. PCANet is an unsupervised feature extraction method based on deep learning theory, which uses PCA to construct the parameters of convolutional filters and retains the hierarchical architecture of traditional convolutional neural networks (CNNs). However, there is limited research on processing EEG signals using PCANet. Combining PCANet with Fast Fourier Transform (FFT) allows an accurate understanding of EEG [7]. The FFT-based deep feature learning method consists of three stages: matrix generation, feature learning, and feature classification. In the first stage, the original EEG signal is reshaped into a matrix in the frequency domain view by FFT. In the second stage, 2D-PCANet is utilized to automatically learn and discover the features ingrained in the generated coefficient matrix in order to efficiently capture the differences between various EEG types. Finally, a support vector machine (SVM) is executed during the classification process to assign labels to each extracted PCANet feature [8].

4. Challenges and future directions

Fast Fourier Transform (FFT) plays an important role as a powerful mathematical tool in biomedical engineering. However, there are a series of challenges and future development opportunities in its application.

First, the application of FFT in biomedical signal processing faces the challenge of computational load. Biomedical signals usually contain a large amount of data, which needs to be processed efficiently and accurately in order to obtain critical information in a timely manner. Although the FFT algorithm is more efficient compared to the traditional Fourier transform, the computational complexity is still high when dealing with extremely large-scale data. Therefore, optimizing FFT algorithms to reduce computation time and resource consumption is an important topic.

Second, the real-time requirement is another key challenge in biomedical applications. In many biomedical applications, such as electrocardiogram (ECG) monitoring and electroencephalogram (EEG) analysis, real-time processing of signals is required for rapid diagnosis or intervention decisions. Improving the real-time processing capabilities of FFT algorithms to meet the needs of these applications is a focus of research.

In the future, the development of FFT technology in the biomedical field will have a broad direction. On the one hand, the development of new algorithms will be key. For example, by using parallel computing and optimized algorithm structure, the computation time of FFT can be further reduced and the processing speed can be improved. On the other hand, the combination of FFT technology with machine learning and artificial intelligence portends great potential. Machine learning algorithms can help improve the accuracy and efficiency of FFT in signal processing, especially in noise filtering and feature extraction.

5. Conclusion

In conclusion, this paper has extensively explored the Fast Fourier Transform (FFT) in the realm of biomedical engineering, underscoring its significant impact and multifaceted applications. Initially, we briefly introduced the concept and historical background of FFT, setting the stage for a deeper understanding of its pivotal role in biomedical engineering.

The mathematical foundation of FFT, rooted in the principles of Discrete Fourier Transform (DFT), was discussed in detail. The algorithm's ability to optimize DFT calculations, highlighted by its computational complexity of O(N log N), represents a significant advance over traditional methods. This section also introduced fundamental signal processing concepts like the frequency domain and sampling theorem, which are crucial in understanding FFT's applications.

The core of the paper focused on the practical applications of FFT in processing biomedical signals, particularly in ECG and EEG signal analysis. For ECG signals, we explored how FFT aids in analyzing frequency components, crucial for diagnosing arrhythmias and myocardial ischemia, and in noise reduction, particularly for eliminating power line interference. In the realm of EEG, FFT's role in analyzing brain waves and detecting neurological disorders such as epilepsy was discussed. Additionally, the application of FFT in differentiating frequency characteristics of various brain activities, contributing to areas like sleep quality analysis, was elaborated.

However, the implementation of FFT in biomedical engineering is not without challenges. The computational load and the demand for real-time processing in signal analysis were identified as major hurdles. Despite these challenges, the paper delved into the future prospects of FFT in this field, suggesting avenues like the development of new algorithms and integration with machine learning techniques.

In sum, the application of FFT in biomedical engineering is a testament to its transformative impact on medical technology. The continued research and development of FFT and related technologies are crucial in advancing this field. This paper not only summarizes FFT's current applications but also emphasizes the importance of ongoing exploration in this domain. The potential for future breakthroughs in biomedical signal processing and imaging, with FFT at the forefront, opens up new horizons for improving medical diagnostics and patient care.

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