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Oversampling Technology and Its Applications in Biomedical Signal Detection

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Abstract: This paper deeply explores oversampling technology and its applications in biomedical signal detection. It first expounds on the significance of oversampling technology in biomedical signal detection, and then analyzes the application strategies of oversampling technology in this field. On this basis, it details the specific applications of oversampling technology in electrophysiological signal detection, biomedical imaging signal processing, and other biomedical signal detections, and verifies its effectiveness through practical case analysis, aiming to provide certain references for relevant researchers.

Keywords: Oversampling technology; Biomedical signal detection; Application strategies

1. Introduction

To advance biomedical innovation, it is essential to strengthen support systems for both basic and applied basic research. This includes promoting original breakthroughs in core theoretical areas and key enabling technologies, particularly in cutting-edge fields. Strategic scientific and technological institutions, such as universities, research institutes, innovation platforms, and leading tech enterprises in Wuxi, are encouraged to deepen their presence in foundational biomedical disciplines and actively participate in major national initiatives and key R&D programs.

Support will be directed toward pre-clinical R&D of innovative medical devices and drugs with independent intellectual property, especially those addressing critical clinical and market needs. Emphasis will be placed on the development of core technologies in cell and gene therapy, modern traditional Chinese medicine, antibody and immune therapies, proteomics, metabolomics, synthetic biology, AI-driven drug discovery, isotope pharmaceuticals, as well as medical imaging, in-vitro diagnostics, intelligent healthcare, implants, surgical robotics, and skin health.

Priority will be given to high-tech research projects with strong industrial relevance and significant economic and social impact. A quarterly joint meeting system will be established to promote the integrated development of biomedical research institutions and enterprises in Wuxi. Medical and health institutions will be encouraged to build cooperative mechanisms with universities, research organizations, and pharmaceutical leaders. Additionally, the development of integrated “industry–medicine–research–application” research hospitals or model wards will be supported, leveraging qualified medical institutions [1].

Researchers are expected to align with national policy guidelines and strategic development goals to better cultivate scientific talent and drive innovation.

2. Significance of oversampling technology in biomedical signal detection

2.1. Reconstructing the physiological signals’ temporal-spatial resolution boundary to achieve precise deconstruction of micro-pathological features

The transience of biomedical signals and tissue heterogeneity requires detection technologies to have sub-millisecond-level time-capturing capabilities and micron-level spatial-positioning accuracy. Taking neural electrical activity as an example, epileptic focus discharges often present as sharp-wave-spike-wave complexes with amplitudes in the μV range and durations in the millisecond range. Traditional devices are prone to aliasing high-frequency oscillations (HFOs) as baseline noise due to sampling rate limitations. However, oversampling technology can clearly separate the multiple-frequency components generated by the synchronous discharges of neuron clusters by increasing the sampling density, revealing their topological relationships with brain-region functional networks and providing electrophysiological markers beyond MRI morphological images for epileptic focus localization [2].

In hemodynamic monitoring, the reconstruction of the spatio-temporal trajectory of the pulse wave conduction depends on the precise analysis of the differences in pressure wave propagation speeds (such as primary waves and reflected waves). Oversampling technology, through high-frequency continuous acquisition and combined with multi-scale wavelet analysis, can separate the waveform distortions caused by micro-structural changes such as vascular wall elasticity and branch angles. This detailed description of hemodynamic details enables the early diagnosis of arteriosclerosis to shift from blood vessel lumen diameter measurement to the assessment of vascular wall mechanical properties. Furthermore, in cell calcium signal detection, oversampling technology can capture calcium spark events triggered by a single action potential. These events last only tens of milliseconds and have a spatial diffusion range of less than 10 μm. This super-resolution detection ability provides direct evidence for revealing pathological mechanisms such as abnormal excitation-contraction coupling in cardiomyocytes and changes in neuronal synaptic plasticity, promoting disease diagnosis from the organ/tissue level to sub-cellular functional units [3].

2.2. Solving the problem of cross-coupling of multimodal signals and constructing a full-dimensional digital mirror of physiological states

Modern medicine is evolving from single-parameter detection to the integration of multi-dimensional physiological atlases, and oversampling technology has become the core hub for achieving spatio-temporal decoupling of multimodal signals. In the field of wearable health monitoring, signals such as heart rate, blood oxygen, and motion artifacts severely overlap in the frequency domain. Traditional synchronous sampling leads to parameter interference due to insufficient sampling rates. However, oversampling technology can configure independent high-frequency acquisition modules for each channel, and combined with tensor decomposition and blind source separation algorithms, it can separate independent components such as PPG waveform modulation induced by respiration and baseline drift caused by motion, achieving precise decoupling of multiple parameters in complex dynamic environments [4]. This ability is particularly crucial in sleep apnea monitoring. By synchronously sampling electrocardiogram, respiration, and body movement signals, the system can distinguish between the different physiological response patterns caused by central sleep apnea (CSA) and obstructive events (OSA). The former is characterized by a sudden interruption of the respiratory drive signal, while the latter is accompanied by paradoxical chest-abdominal movements. This classification mechanism, based on the temporal characteristics of multimodal signals, increases the diagnostic accuracy by 40% compared to single-channel detection [5].

In the intensive care scenario, oversampling technology promotes the transformation of hemodynamic monitoring from static parameter measurement to dynamic system modeling. By parallelly collecting multiple signals such as electrocardiogram, arterial pressure, and central venous pressure, and combined with dynamic mode decomposition and manifold learning algorithms, a low-dimensional dynamic model of the cardiovascular system can be constructed, revealing the differences in baroreceptor reflex arcs and volume regulation mechanisms in different types of shock (such as cardiogenic and septic shock), providing real-time decision-making support for individualized fluid resuscitation strategies [6].

2.3. Driving the evolution of biomedical digital twins and forming a disease prediction-intervention closed-loop

The ultra-dense data stream generated by oversampling technology provides an accurate mapping from the physical world to the digital space for constructing high-fidelity biomedical digital twins. In the field of cardiac electrophysiology, high-density electrode arrays on the body surface are used for high-frequency oversampling. Combined with the boundary element method and deep neural networks, a three-dimensional spatio-temporal map of cardiac activation conduction can be reversely reconstructed. The resolution is sufficient to track the dynamic evolution of a single re-entry loop. This digital reproduction ability of arrhythmia mechanisms transforms radiofrequency ablation from an empirical operation to a precise intervention based on a virtual lesion model. In the monitoring of tumor immunotherapy, oversampling technology has promoted the construction of an early warning system for cytokine storms.

Through continuous high-frequency detection of key factors such as IL-6 and TNF-α using microfluidic chips, and combined with graph neural network analysis of the topological changes in the cytokine network, the critical point of immune response out-of-control can be identified in advance. The prediction model can not only capture the absolute changes in cytokine concentrations but also analyze the dynamic reconstruction of the synergistic/antagonistic relationships between signal molecules. This real-time modeling ability of the immune micro-environment evolution enables doctors to initiate interventions 8–12 hours before the occurrence of cytokine release syndrome (CRS). More profoundly, oversampling technology endows digital twins with self-evolution capabilities. By continuously accumulating individualized patient data, the algorithm can dynamically optimize model parameters, continuously improving the prediction accuracy of virtual organ responses to treatment over time, ultimately forming a complete “detection-modeling-intervention-feedback” closed-loop and promoting the transformation of medicine from passive treatment to proactive health management [7].

3. Application strategies of oversampling technology in biomedical signal detection

3.1. Applications in electrophysiological signal detection

Users of oversampling technology can improve the detection accuracy and dynamic range by sampling at a rate far exceeding the Nyquist frequency. For example, in electrocardiogram (ECG) signal detection, users can use a sampling rate of 200 kHz to sample a conventional 1 kHz-bandwidth signal 1024 times. This disperses the noise into the 0–512 kHz frequency band, while the signal energy is concentrated in the 0–1 kHz band [8]. The quantization error of 1 LSB (about 0.24 mV) in a traditional 12-bit ADC can minimize minor features such as P-waves and T-waves. However, current oversampling technology can improve the equivalent resolution through sampling superposition and digital filtering, better enabling the detection of ST-segment shifts and capturing pathological features. For example, a team from Tianjin University not only amplified the ECG signal above the quantization threshold of the ADC by superimposing a triangular-wave-shaped signal but also combined 1024-fold oversampling with moving-average filtering to expand the range of the ECG signal to ± 5 mV, effectively suppressing 50 Hz electromyographic noise.

In the coordination of oversampling and noise-shaping technology, their combination can increase the signal-to-noise ratio, which is then applied in epilepsy diagnosis. In implantable neural recording, oversampling technology, with a 16-bit ADC and 4096-fold oversampling, can increase the equivalent resolution to 20 bits while maintaining a power consumption level of μW, meeting the detection requirements of action potentials (50–100 μV) of visual cortex neurons for retinal prostheses. In the combination of oversampling and compressive sensing theory, sub-sampling of ECG signals can be achieved through random projection to meet the battery-life requirements of wearable ECG monitoring devices [9]. It can be seen that the applications of oversampling technology in electrophysiological signal detection are reflected in different aspects, and only by better developing and utilizing it can the needs of users be met [10].

3.2. Applications in biomedical imaging signal processing

Oversampling technology can break through the limitations of physical sampling and reconstruct signals, thus improving the ability of medical images to analyze the micro-structure and pathological features of biological tissues [11]. Oversampling technology can achieve rapid performance development through the following methods: First, the combination of oversampling technology and synthetic aperture focusing technology (SAFT) can reduce the resolution of ultrasonic pulses from 6.25 ns to 1.56 ns, improving the detection sensitivity of thyroid nodule imaging and facilitating better treatment. Second, in the lateral direction, the oversampling technology achieves 16-fold oversampling through the time-division excitation of the transmitting sub-arrays, which can be better applied to breast mass detection. Third, users can use complex-domain oversampling technology to better capture the amplitude and position information of echo signals, facilitating the location of hemangiomas and small liver cancers for better treatment. For example, in the field of elastography, users can reduce the measurement standard deviation of shear-wave velocity (SWV) through oversampling and SWV tracking, and better apply it to the grading of liver cirrhosis for better clinical medicine [12]. The applications of oversampling technology in biomedical imaging signal processing have expanded in different directions, and only by better using it can the efficiency of users be improved [13].

3.3. Applications in other biomedical signal detections

Human blood pressure exhibits multi-scale fluctuation characteristics in circadian rhythms, postural changes, and emotional stress. Traditional blood pressure monitoring devices, limited by sampling rates (usually < 200 Hz) and data compression mechanisms, have difficulty capturing the transient responses of baroreceptor reflex arc regulation (such as the 30 mmHg/s rapid pressure change caused by the Valsalva maneuver) and the subtle distortions of pressure wave conduction (such as the 0.5-ms-level reflection time-delay difference at the aortic branch) [14]. Oversampling technology, by increasing the sampling rate to the kHz level and combined with the steep roll-off characteristics of anti-aliasing filters (blocking attenuation ≥ 80 dB/oct), can analyze the hidden dynamic features in blood pressure signals. In 24-hour dynamic monitoring, high-frequency sampling data can clearly record the sub-second-level transition process of blood pressure from the resting state to the stress state, revealing the real-time shift of the sympathetic-parasympathetic balance in autonomic nerve regulation.

This millisecond-level tracking ability of baroreceptor sensitivity (BRS) enables the analysis of blood pressure variability (BPV) to shift from static parameter statistics to dynamic system modeling. By extracting non-linear features such as the depth change of the pulse notch in the blood pressure waveform and the spatio-temporal distribution of the pulse wave velocity, oversampling technology can quantify the heterogeneity of the elastic modulus of the arterial tree, identifying the early signs of vascular remodeling 12–18 months earlier than traditional methods and providing biomarkers beyond mean arterial pressure for early warning of hypertensive target-organ damage. More importantly, the oversampling data stream supports the construction of a digital twin of the cardiovascular system. By performing multi-modal fusion analysis of continuous blood pressure signals with electrocardiogram and respiration signals, the closed-loop regulatory network of cardio-pulmonary coupling can be reconstructed, revealing the phase-locking relationship between respiratory sinus arrhythmia (RSA) and blood pressure fluctuations. This dynamic modeling ability of the neuro-humoral regulation mechanism enables cardiovascular risk assessment to shift from organ morphological judgment to physiological function network analysis [15].

4. Conclusion

This paper deeply explores the significance of oversampling technology in biomedical signal detection and its application strategies, aiming to provide certain references for relevant researchers, contribute to the development of this field, and encourage more people to join the research in this area.

Disclosure statement

The author declares no conflict of interest.

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