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應用於即時帕金森氏症控制之閉迴路生醫訊號處理電路設計與實現

Design and Implementation of a Closed-Loop Biomedical Signal Processing Circuit for Real-Time Parkinson's Disease Control

研 究 生：袁鈺彬 (Yuan, Yu-Pin)

指導教授：柯明道 (Ker, Ming-Dou)

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應用於即時帕金森氏症控制之閉迴路
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摘要

帕金森氏症是一種退化性神經疾病，隨著人口逐漸高齡化，其盛行率也持續攀升。為了因應未來患者人數增加的趨勢，本論文提出應用於帕金森氏症即時控制的閉迴路生醫訊號處理電路，能即時監測腦部 β 波活動，並控制深腦刺激器的啟動時機。

相較於在臨床上被驗證的演算法，本設計在頻率域上進行訊號處理以估測 β 振幅，省去時域演算法所需的額外濾波器，進而減少整體運算量以及硬體資源需求，並結合 Welch's method 進行 β 峰追蹤，取代前一版電路所使用的直方圖方法，不僅提升偵測穩定性與準確度，且可重複利用先前計算之頻譜，無需額外運算。模擬結果顯示，與臨床驗證演算法相比，本系統可達成 0.85 的相關性係數與 90% 的刺激時機準確率。

整體系統架構包括快速傅立葉轉換（FFT）、β 峰追蹤器、刺激判斷、長期記錄器、參數記憶體和通用非同步收發傳輸器（UART）介面。考量植入式系統單晶片（SoC）中資源受限的特性，為實現低功耗與小面積目標，本研究針對 FFT 核心進行演算法與硬體架構優化，包含使用 CFFT packing 降低在進行實數序列轉換時的運算量和記憶體需求，以及利用 cached-memory 架構減少主記憶體的存

取次數，達到節能的需求。β峰追蹤器及刺激判斷亦新增權重調整機制，以提升系統彈性與參數適應能力。長期記錄器持續蒐集β活動變化，有助於植入後的臨床追蹤與參數調整。參數記憶體和 UART 集中管理系統參數，並提供外部即時監控介面。

為驗證系統功能，本研究將系統部署至現場可程式化邏輯閘陣列（FPGA），並設計偽類比數位轉換器模擬 SoC 中的周邊電路，透過 UART 介面與外部電腦連接，搭配 LabVIEW 撰寫之封包解析與圖形化操作介面，便於開發與測試。

本系統採用 0.18 微米製程實作並整合至 SoC 中。量測結果顯示，系統運行於 1.8V、921.6 kHz 時，偵測延遲每通道約為 866 微秒，平均功耗僅 0.55 mW。此外，在 SoC 中與其他電路整合導致潛在的漏電路徑也有被找出，並提供解決方法。

總結而言，本研究提出的生醫訊號處理電路具備即時 β 活動偵測與參數動態修正能力，能提供準確的刺激控制波形，並以其小面積與低功耗特性，展現應用於長期植入式神經調控系統的實用性。

關鍵詞/字 — 帕金森氏症、植入式裝置、神經調節、深腦刺激、快速傅立葉變換、即時閉迴路深腦電刺激系統單晶片

Design and Implementation of a Closed-Loop Biomedical Signal Processing Circuit for Real-Time Parkinson's Disease Control

Student: Yu-Pin Yuan Advisor: Prof. Ming-Dou Ker

Institute of Electronics
National Yang Ming Chiao Tung University

Abstract

Parkinson's disease is a neurodegenerative disorder, and its prevalence is expected to rise with the global trend of population aging.

To address the growing demand for treatment, this thesis presents a closed-loop biomedical signal processing circuit designed for real-time control in Parkinson's disease applications. The system continuously monitors β-band neural activity and dynamically controls the activation of the deep brain stimulator.

The proposed system operates in the frequency domain to estimate β amplitude, eliminating the need for additional filters and reducing both computational and hardware complexity. Welch's method is integrated for β peak tracking, replacing the histogram-based approach used in the previous design. This enhances detection stability and accuracy while reusing previously computed spectra without additional computational overhead. Simulation results show a correlation coefficient of 0.85 with the clinically validated algorithm and a stimulation accuracy of 90%.

The overall system includes a fast Fourier transform (FFT) module, beta peak tracker, decision-making logic, long-term recorder, parameter memory, and a universal

asynchronous receiver/transmitter (UART) interface. To achieve low power consumption and minimal area, the algorithm and architecture of the FFT core are optimized for resource-constrained implantable system-on-chip (SoC) environments. CFFT packing is used to reduce operations and memory usage for real-valued sequences, and a cached-memory architecture is used to minimize main memory access. The beta peak tracker and decision-making logic are extended with weighted functions to improve flexibility. The long-term recorder continuously logs beta activity for post-implantation tracking, while the parameter memory and UART provide centralized parameter control and real-time system monitoring.

To verify functionality, the system was deployed on an FPGA with a pseudo analog-to-digital converter (ADC) to emulate SoC peripherals. A LabVIEW-based graphical user interface was developed to parse UART packets and facilitate user interaction.

The chip is fabricated in a 0.18-μm CMOS process and integrated into an SoC. Measurement results show a per-channel detection latency of 866 μs, with an average power consumption of 0.55 mW under 1.8 V power supply and 921.6 kHz. Integration-related leakage paths are identified and a solution is also provided.

In summary, the proposed biomedical signal processing circuit enables real-time detection of abnormal beta activity and dynamic parameter adjustment, delivering accurate stimulation control. Its small area and low power make it well-suited for long-term implantable neuromodulation systems.

Keywords – Parkinson's disease (PD), implantable device, neuromodulation, deep brain stimulation (DBS), fast Fourier transform (FFT), real-time closed-loop deep brain stimulation (DBS) system-on-chip (SoC).