

國立陽明交通大學

電子研究所

碩 士 論 文

Institute of Electronics

National Yang Ming Chiao Tung University

Master Thesis

應用於神經調控系統之神經訊號壓縮與處理架構設計

A Neural Signal Compression and Processing

Architecture for Neuromodulation Applications

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中 華 民 國 一 一 五 年 七 月

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A Thesis

Submitted to

Institute of Electronics

College of Electrical and Computer Engineering

National Yang Ming Chiao Tung University

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in

Electronics Engineering

July 2026

Hsinchu, Taiwan, Republic of China

中 華 民 國 一 一 五 年 七 月

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摘要

深腦刺激 (Deep Brain Stimulation, DBS) 為一種透過電刺激調控神經活動的治療技術，已應用於帕金森氏症等神經退化性疾病。隨著植入式神經調控系統之感測通道數、取樣頻率與長期記錄需求增加，神經訊號傳輸所需之資料量亦隨之提升，使資料傳輸頻寬與系統功耗成為重要設計限制。閉迴路深腦刺激系統可根據即時量測之神經生物標記調整刺激參數，以提升刺激控制之適應性與能源效率。然而，大量神經訊號的持續傳輸仍可能限制植入式系統之記錄時間與通訊效率，因此有必要於資料傳輸前進行低複雜度且低失真的訊號壓縮。

由於局部場電位 (Local Field Potential, LFP) 包含重要的生理資訊，本研究以可完整重建原始資料之無損壓縮為主要設計目標，提出一套應用於神經訊號傳輸之 Deflate 壓縮 ASIC。Deflate 結合 LZ77 與 Huffman Coding，其中 LZ77 透過長度與距離資訊取代資料流中重複出現之字串，而 Huffman Coding 則根據符號統計特性配置不同碼長，以降低資料之統計冗餘。本研究進一步採用 Canonical Huffman Coding，依據既有碼長與符號順序以規則化方式產生碼字，使編碼器僅需儲存碼長與相關查找資訊，進而降低完整霍夫曼樹所需之記憶體與控制複雜度。

在硬體架構方面，本研究採用雜湊式 LZ77 字典搜尋、雙埠記憶體與寫入緩衝機制，以提升重複字串搜尋與字典更新效率；後端則採用 Two-Pass Dynamic

Canonical Huffman Coding，並以先進先出緩衝器協調各處理階段之資料流。針對較小資料區塊，系統亦支援 Static Huffman Coding，以避免動態碼表建立及標頭資訊所造成之額外負擔。所提出之壓縮系統可輸出符合 GZIP 格式之資料流，並透過循環冗餘檢查碼（Cyclic Redundancy Check, CRC）驗證解壓縮資料之完整性。

除神經訊號壓縮外，本研究亦針對既有神經訊號處理與刺激平台進行功能改良。快速傅立葉轉換（Fast Fourier Transform, FFT）模組採用管線化與區塊浮點運算架構，以在數值動態範圍、運算精度及硬體成本之間取得折衷，並支援帕金森氏症相關 β 頻帶神經活動之頻譜分析。此外，為避免刺激振幅快速切換所造成之可感知刺激與暫態副作用，本研究設計可調式刺激斜坡控制器，使刺激振幅可依不同目標振幅與斜坡時間逐步上升或下降。

功能驗證方面，壓縮架構分別透過 FPGA 與 0.18 μm CMOS 製程完成實作與驗證；測試資料由 FPGA 內部 Block RAM 輸入，並利用內建邏輯分析儀擷取壓縮輸出。晶片量測結果顯示，壓縮系統可於 1.8 V 供應電壓下正常運作，於所測試之神經訊號資料集達到 5.1 倍壓縮比，平均功耗為 4.27 mW。FFT 與刺激斜坡控制器則整合至既有神經活性監測與刺激 FPGA/SoC 驗證平台，透過偽類比數位轉換器、UART 與 LabVIEW 圖形化介面完成系統功能測試。

總結而言，本研究以神經訊號無損壓縮 ASIC 為主要貢獻，並完成 FFT 運算架構與刺激斜坡控制之功能改良。所提出之設計可降低神經訊號傳輸所需資料量，並提升神經訊號分析與刺激控制之硬體實作彈性，作為未來長時間神經訊號記錄及高整合度神經調控系統之基礎。

關鍵詞/字 — Deflate、無損壓縮、神經訊號、深腦刺激、快速傅立葉轉換、刺激斜坡控制。

A Neural Signal Compression and Processing Architecture for Neuromodulation Applications

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Abstract

Deep brain stimulation (DBS) is a neuromodulation therapy that has been applied to neurodegenerative disorders such as Parkinson's disease. As the number of sensing channels, sampling rate, and long-term recording requirements of implantable neuromodulation systems continue to increase, the resulting data volume imposes significant constraints on transmission bandwidth and system power consumption. Therefore, a low-complexity compression architecture is required to reduce the amount of neural data prior to transmission while preserving the information required for subsequent analysis.

Because local field potential (LFP) signals contain valuable physiological information, this work focuses on lossless compression to ensure exact reconstruction of the original data. A Deflate-based compression ASIC is proposed for neural signal transmission. Deflate combines LZ77 and Huffman coding. LZ77 replaces repeated data sequences with length-distance pairs, whereas Huffman coding assigns variable-length codes according to symbol statistics to reduce statistical redundancy. Canonical Huffman coding is further adopted to generate codewords systematically according to the assigned code lengths and symbol order. Consequently, only the code lengths and

associated lookup information need to be stored, reducing the memory requirements and control complexity associated with a complete Huffman tree.

The proposed compression architecture employs hash-based dictionary searching, dual-port memory, and a write-buffer mechanism to improve the efficiency of repeated-string matching and dictionary updates. A two-pass dynamic canonical Huffman coding architecture is implemented in the back end, while first-in, first-out buffers are used to coordinate the data flow among processing stages. Static Huffman coding is also supported for small data blocks to avoid the code-table construction and header overhead associated with dynamic coding. The proposed system generates a GZIP-compliant output bitstream, and a cyclic redundancy check is used to verify the integrity of the reconstructed data.

In addition to neural signal compression, this work improves the signal-processing and stimulation-control functions of an existing neuromodulation platform. The fast Fourier transform (FFT) module employs pipelined and block floating-point architectures to achieve a balance among numerical dynamic range, computational accuracy, and hardware cost. The module supports spectral analysis of beta-band neural activity associated with Parkinson's disease. Furthermore, a programmable stimulation-ramping controller is developed to gradually increase or decrease the stimulation amplitude according to the target amplitude and ramp duration, thereby reducing perceptible stimulation and transient side effects caused by abrupt amplitude changes.

The compression architecture was implemented and verified using both an FPGA platform and a 0.18- μm CMOS process. Neural data stored in the FPGA block RAM were used as the input, and the compressed output was captured using an integrated logic analyzer. Chip measurement results demonstrate that the compression system operates correctly at a supply voltage of 1.8 V. For the evaluated neural signal dataset,

the system achieves a compression ratio of $5.1\times$ with an average power consumption of 4.27 mW. The FFT module and stimulation-ramping controller were separately integrated into an existing FPGA/SoC verification platform for neural monitoring and stimulation. System-level functional verification was performed using an analog-to-digital converter emulator, a UART interface, and a LabVIEW-based graphical user interface.

In summary, the primary contribution of this work is a lossless neural signal compression ASIC, supplemented by architectural improvements to FFT processing and stimulation-ramping control. The proposed design reduces the amount of neural data required for transmission and improves the implementation flexibility of neural signal analysis and stimulation control, providing a foundation for long-term neural recording and highly integrated neuromodulation systems.

Keywords — Deflate, lossless compression, neural signal, deep brain stimulation, fast Fourier transform, ramping control.