Expansion of the Hybrid Topological Neural Network for Advanced Brain-Computer Interface Applications: Towards Bi-Directional Communication and the Early Diagnosis of Neurodegenerative Diseases

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Advanced prosthetic technologies have improved mobility for individuals with limb loss, yet restoring natural motor control and sensory perception remains a crucial challenge. Current systems fail clinical translation due to limited multi-degree-of-freedom control. Regenerative Peripheral Nerve Interfaces (RPNIs) transduce residual peripheral nerve activity into electromyographic (EMG) signals, but biological noise, signal overlap, and low specificity prevent precise movement decoding and naturalistic sensory feedback. This study presents a Hybrid Topological Neural Network (HTNN) integrating topological data analysis with deep learning for robust neural decoding, real-time sensory integration, and diagnostic monitoring. HTNN segmented overlapping EMG signals and fused cortical motor planning inputs, achieving multimodal classification accuracies of 96.3% ± 1.2% with sub-85 ms latency for smooth, closed-loop prosthetic control. Sensory feedback integration improved task precision and reduced trajectory errors. Diagnostic simulations emulating neurodegenerative conditions demonstrated dynamic reallocation of predictive weight from motor to cortical signals, maintaining accuracy above 78% under degradation. Persistent homology features preserved multiscale geometric signal structure, enhancing interpretability and resilience over conventional CNN-LSTM models. Ablation and transfer learning studies confirmed topological encoding's role in resolving signal overlap and enabling rapid adaptation across interdisciplinary systems engineering contexts. HTNN establishes a scalable, fault-tolerant platform for bidirectional brain–computer interfaces, advancing clinically deployable systems that improve human lives through artificial intelligence and computational neuroscience.

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