iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: II Month of publication: February 2026

DOI: https://doi.org/10.22214/ijraset.2026.77359

A System-Level Neuromorphic Framework for Closed-Loop Brain-Computer Interfaces toward Restorative Neuroprosthetic Control

Anand Rawat[1], Anamika Yadav[2], Anand Sen[3], Ananya Agarwal[4], Anandi Singh[5]
Department of Computer Science and Engineering, Pranveer Singh Institute of Technology (Affiliated with AKTU), Kanpur, Uttar Pradesh, India

Abstract: Brain–computer interfaces (BCIs) and neuroprosthetic systems have demonstrated significant progress in decoding neural intent and enabling assistive motor and communication functions. However, achieving stable, long-term restoration of motor and autonomic function remains a central challenge in neural engineering, particularly under constraints of power efficiency, latency, and adaptability required for implantable systems. Neuromorphic computing offers a biologically inspired, event-driven computational paradigm that aligns closely with the operational requirements of closed-loop neural interfaces. This paper presents a system-level neuromorphic framework for closed-loop brain–computer interfaces aimed at restorative neuroprosthetic control. Rather than proposing a complete cognitive replacement, the framework is designed as a modular neural bypass that integrates spiking neural networks, bidirectional BCI architectures, and adaptive feedback mechanisms to support motor execution and autonomic regulation. The framework is grounded in established principles of neural engineering, neuroprosthetics, and implantable system design, with explicit consideration of biological integration, long-term stability, and ethical constraints. By articulating a coherent neuromorphic architecture tailored to closed-loop BCI operation, this work aims to provide a foundational reference for future experimental validation and translational development of neuromorphic neuroprosthetic systems within the neural engineering community.
Keywords: neuromorphic computing; brain–computer interfaces; neural rehabilitation; neuroprosthetics; spiking neural networks; closed-loop control; bioelectronic medicine

I. INTRODUCTION

Severe neurological impairment resulting from traumatic brain injury, ischemic stroke, neurodegenerative disease, or hypoxic events frequently disrupts the communication pathways between cortical decision-making centers and peripheral motor and autonomic systems. Patients affected by such conditions may retain partial or latent cognitive function while losing the ability to translate intent into physical action, leading to profound loss of autonomy and quality of life.

Contemporary neuroprosthetic technologies have demonstrated meaningful progress in restoring limited function, particularly in communication and assisted motor control. Brain–computer interfaces (BCIs) have enabled paralyzed individuals to control cursors, robotic limbs, and speech synthesizers through decoded neural activity. However, most existing systems operate as assistive overlays rather than functional neural substitutes, requiring continuous user effort and external supervision. Neuromorphic computing introduces a complementary paradigm that aligns closely with the operational principles of biological neural systems. By employing event-driven computation, distributed memory, and adaptive learning, neuromorphic architectures offer a pathway toward low-power, continuous neural processing suitable for implantable medical devices. The convergence of BCIs and neuromorphic hardware creates an opportunity to move beyond episodic assistive control toward persistent, autonomous functional restoration. This paper proposes a neuromorphic brain–chip interface framework designed to operate as a modular neural bypass rather than a full cognitive replacement. The framework emphasizes closed-loop interaction, adaptive learning, and physiological compatibility, with the goal of supporting both voluntary motor execution and autonomic regulation. Rather than presenting a finished clinical solution, this work aims to define a technically grounded system-level architecture that is valuable at the current stage of the field, where hardware capabilities, implantable neuromorphic platforms, and closed-loop BCI methodologies are rapidly converging.

Such framework-driven studies play an important role in neural engineering by informing experimental design, hardware–software co-development, and translational research directions. Accordingly, this study includes a minimal computational formulation to establish closed-loop feasibility at the system level, while deferring quantitative evaluation to future experimental work.

A . Novelty and Contribution

The primary contribution of this work is the formulation of a unified neuromorphic framework explicitly tailored to closed-loop brain–computer interfaces and restorative neuroprosthetics. In contrast to existing BCI architectures that primarily emphasize neural signal decoding or task-specific assistive output, the proposed framework integrates neuromorphic computing as a core architectural element enabling continuous, adaptive neural bypass control.

Neuromorphic computing is positioned not as an optional accelerator but as a necessary computational paradigm for implantable-scale systems, providing event-driven processing, low-power operation, and inherent temporal alignment with biological neural dynamics. By introducing a modular "digital brainstem" abstraction implemented through spiking neural networks, this work provides system-level guidance that is directly relevant to the design of next-generation closed-loop neuroprosthetic systems within the neural engineering community.

II. NEUROMORPHIC COMPUTING FOR IMPLANTABLE SYSTEMS

A. Spiking Neural Networks and Event-Driven Processing

Spiking neural networks (SNNs) form the computational core of neuromorphic systems and are characterized by sparse, event-driven signaling that closely resembles biological neuronal activity. Unlike conventional artificial neural networks that rely on continuous-valued activations and clock-driven computation, SNNs process information through discrete spike events, enabling temporal encoding and energy-efficient operation.

This event-driven paradigm is particularly advantageous for implantable neuroengineering applications, where power dissipation and thermal constraints directly impact patient safety. By activating computation only when relevant neural events occur, neuromorphic processors can operate continuously at power levels compatible with long-term implantation.

In addition to efficiency, SNNs support local learning mechanisms such as spike-timing-dependent plasticity (STDP), enabling adaptive recalibration in response to non-stationary neural signals. This adaptability is essential for chronic BCIs, where neural signal characteristics evolve over time due to biological plasticity, electrode micromotion, and tissue response.

B. Neuromorphic Hardware Platforms and Constraints

Recent neuromorphic platforms, including IBM TrueNorth, Intel Loihi, and SpiNNaker systems, demonstrate the feasibility of large-scale neural emulation with milliwatt-level power consumption. These platforms integrate memory and computation at the synaptic level, enabling massively parallel processing with minimal data movement.

For implantable systems, however, several constraints remain critical. Chip form factor, biocompatibility, thermal dissipation, and long-term reliability must be considered alongside computational performance. While current neuromorphic hardware is primarily developed for research and edge computing, ongoing miniaturization and packaging advances suggest a realistic pathway toward implantable variants.

Standardization and benchmarking remain open challenges within the neuromorphic field.

Nevertheless, the demonstrated efficiency and adaptability of existing platforms establish a credible foundation for future neuroprosthetic integration.

III. BRAIN–COMPUTER INTERFACES AND CLOSED-LOOP CONTROL

A. Neural Interface Modalities

BCI systems acquire neural signals through a range of interface modalities, each presenting a distinct trade-off between signal fidelity, invasiveness, and long-term viability. Invasive microelectrode arrays provide high spatial and temporal resolution but introduce risks related to surgical implantation, foreign-body response, and signal degradation over time.

Non-invasive techniques such as electroencephalography offer improved safety and accessibility but suffer from reduced spatial specificity and susceptibility to noise. Semi-invasive and emerging modalities aim to balance these factors, enabling stable neural access while reducing biological disruption.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue II Feb 2026- Available at www.ijraset.com

The proposed framework is modality-agnostic, allowing adaptation to different clinical contexts and technological maturity levels.

B. Bidirectional and Adaptive Closed-Loop BCIs

Functional restoration requires continuous interaction between neural intent, system output, and sensory feedback. Closed-loop BCIs enable this interaction by incorporating feedback pathways that refine system behavior in real time. Without feedback, motor commands remain imprecise and unstable, particularly for complex or sustained tasks.

Neuromorphic processing is well suited for closed-loop control due to its low latency and event-driven nature. By integrating sensory feedback directly into the spiking network, the system can adaptively tune output commands, supporting smoother motor execution and physiological stability.

Such closed-loop architectures represent a critical transition from assistive decoding systems to autonomous neuroprosthetic controllers.

IV. PROPOSED NEUROMORPHIC FRAMEWORK

The proposed neuromorphic brain–chip interface is designed as a modular neural bypass that operates in parallel with preserved biological circuitry. Rather than attempting to replicate higher cognitive processes, the framework focuses on restoring disrupted sensorimotor and autonomic pathways through adaptive control.

A. System Architecture

The framework comprises four primary layers:

1) Neural acquisition layer for recording cortical or subcortical activity
2) Neuromorphic processing layer implementing spiking neural computation
3) Control and actuation layer interfacing with peripheral nerves or muscles
4) Sensory feedback layer providing real-time physiological input

Each layer operates semi-independently, enabling incremental deployment and validation.

B. Digital Brainstem Concept

In this framework, the digital brainstem is defined as a neuromorphic control module that implements low-level sensorimotor and autonomic regulation through closed-loop spiking computation. Rather than serving as a metaphorical construct, the digital brainstem is treated as an explicit engineering subsystem with well-defined inputs, outputs, and adaptation mechanisms.

Inputs to the digital brainstem consist of spike-based neural activity acquired from preserved cortical or subcortical regions, along with sensory and physiological feedback signals encoding motor state, proprioception, or autonomic variables. Outputs are expressed as control vectors driving peripheral effectors, including skeletal muscle activation or autonomic actuation.

Functionally, this module is analogous to biological brainstem circuits that mediate reflexive motor coordination and homeostatic regulation. By targeting these low-level control pathways, the framework avoids replication of higher cognitive processes while enabling stable and continuous bodily function. This formalization allows the digital brainstem to be treated as a control-theoretic entity amenable to analytical reasoning and system-level validation.

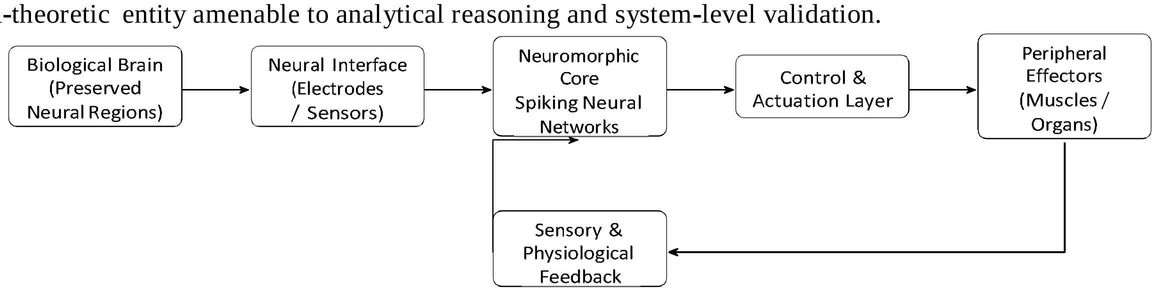


Figure 1. Block diagram of the proposed neuromorphic brain–chip interface. Neural signals from preserved brain regions are acquired via a neural interface and processed by a neuromorphic computing core based on spiking neural networks. Decoded intent is translated into motor and autonomic control signals delivered to peripheral effectors.

Continuous sensory and physiological feedback is reintegrated into the neuromorphic core, enabling adaptive closed-loop control. The system operates as a modular neural bypass rather than a full cognitive replacement. Spike-based neural signals, decoded control outputs, and sensory feedback pathways are explicitly represented to emphasize closed-loop neuromorphic control.

C. System-Level Feasibility Considerations

Although the proposed framework is conceptual, its feasibility can be qualitatively assessed using established principles from neural engineering and control theory. Neuromorphic processing supports low-latency operation due to localized computation and event-driven signal propagation, reducing delays that can destabilize closed-loop neuroprosthetic control.

Power efficiency arises from sparse spiking activity and in-memory computation, making continuous operation compatible with implantable energy constraints. Adaptability is supported through local learning mechanisms within spiking neural networks, allowing compensation for neural signal drift, electrode micromotion, and long-term biological plasticity.

Closed-loop stability is further enhanced by direct integration of sensory and physiological feedback into the neuromorphic processing layer, reducing reliance on external supervisory control. Together, these characteristics provide a strong system-level justification for the framework as a viable neural engineering architecture suitable for future experimental validation.

V. COMPUTATIONAL AND THEORETICAL VALIDATION

To support the feasibility of the proposed framework beyond conceptual description, we introduce a minimal in silico closed-loop model that captures the essential dynamics of neuromorphic control without claiming experimental performance. The purpose of this validation is to demonstrate that the digital brainstem architecture admits stable, adaptive closed-loop operation under realistic neural engineering assumptions.

A. Closed-Loop Spiking Control Formulation

The neuromorphic core is modeled as a recurrent spiking neural network (SNN) receiving input spike trains $\mathbf{x}(t)$ from preserved neural regions and sensory feedback signals $\mathbf{f}(t)$. Network dynamics are governed by event-driven membrane evolution, while output spike trains $\mathbf{y}(t)$ are decoded into continuous control signals $\mathbf{u}(t)$ through population-based rate decoding.

The closed-loop system is described by:

$$\mathbf{u}(t) = \mathrm{D}(\mathbf{y}(t)), \quad (1)$$

$$\mathbf{y}(t) = \mathrm{S}(\mathbf{x}(t), \mathbf{f}(t), \mathbf{w}(t)), \quad (2)$$

where $\mathrm{S}(\cdot)$ represents spiking network dynamics, $\mathrm{D}(\cdot)$ denotes the decoding operator, and $\mathbf{w}(t)$ denotes adaptive synaptic weights.

Synaptic adaptation follows a local learning rule of the form:

$$\Delta\mathbf{w} \propto \eta\, \Phi(\Delta t, r(t)), \quad (3)$$

where $\Phi(\cdot)$ represents spike-timing-dependent or reward-modulated plasticity, $r(t)$ denotes a scalar feedback or error-related signal, and η is a learning rate. This formulation allows the network to adapt to non-stationary neural inputs and interface drift without centralized supervision.

B. Stability, Latency, and Power Considerations

Closed-loop stability can be qualitatively assessed by noting that feedback signals $\mathbf{f}(t)$ are integrated directly into the spiking dynamics, reducing phase lag associated with external supervisory control. Under bounded input activity and finite synaptic weights, network firing rates remain bounded, supporting stable control output in expectation.

Latency is dominated by spike transmission and local synaptic integration rather than global clocked computation. For biologically plausible firing rates, neuromorphic event-driven processing supports response times compatible with sensorimotor and autonomic control loops. Power efficiency arises from sparse spiking activity and in-memory computation, enabling continuous operation under implantable energy constraints. While no numerical benchmarks are claimed, the architectural properties align with established neuromorphic platforms designed for low-power neural processing.

This minimal computational validation does not aim to quantify performance but establishes that the proposed digital brainstem framework constitutes a well-posed closed-loop neural engineering system suitable for future simulation, hardware implementation, and experimental evaluation.

From a control-theoretic perspective, the proposed formulation constitutes a bounded adaptive feedback system in which neural inputs, synaptic weights, and firing rates are constrained by biological and hardware limits. Under these conditions, the closed-loop mapping from sensory feedback to control output remains well-defined, and unbounded growth of network activity is avoided in expectation. While a formal Lyapunov analysis is beyond the scope of this work, the architecture aligns with established principles of stable adaptive control in neural systems.

VI. BIOLOGICAL INTEGRATION AND MATERIAL CONSTRAINTS

Long-term neural implantation is constrained by the brain's foreign-body response, characterized by inflammation, gliosis, and progressive signal degradation. Mechanical mismatch between rigid electronic components and soft neural tissue exacerbates these effects, limiting implant longevity.

Recent advances in flexible polymers, hydrogel-based interfaces, and biomimetic electrode designs offer promising mitigation strategies. Tissue-compliant substrates reduce micromotion damage and promote stable neural integration, while surface functionalization can modulate immune response.

Effective neuromorphic neuroprostheses must therefore be co-designed across materials science, neuroscience, and electronic engineering domains to ensure both functional performance and biological compatibility.

VII. ETHICAL AND CLINICAL CONSIDERATIONS

Neuromorphic brain–chip interfaces raise ethical considerations related to autonomy, agency, and the boundary between therapeutic restoration and cognitive enhancement. While the proposed framework prioritizes restoration of lost function, adaptive systems capable of autonomous decision-making necessitate transparent oversight mechanisms.

Clinical deployment must address informed consent, particularly for patients with impaired consciousness or cognitive capacity. Long-term psychological effects, identity perception, and dependence on artificial control systems require systematic study. Equitable access and responsible governance are essential to prevent the emergence of socioeconomic disparities in access to advanced neurotechnologies.

VIII. LIMITATIONS AND FUTURE WORK

The framework presented in this study is conceptual and system-oriented rather than experimentally validated, which represents an important limitation. While grounded in current neuromorphic and BCI research, the proposed architecture has not yet been implemented in hardware or evaluated in vivo. As such, performance metrics related to latency, stability, and long-term adaptability remain to be quantified.

Biological integration poses additional challenges. Chronic implantation is limited by foreign-body response, electrode degradation, and neural plasticity that may alter signal characteristics over time. Although advances in flexible and biomimetic materials provide promising mitigation strategies, long-term stability remains an open research problem.

Future work will focus on progressive validation of the framework through hardware prototyping and closed-loop simulation. Initial efforts may involve benchtop neuromorphic processors interfaced with synthetic neural data, followed by preclinical studies evaluating adaptive motor control. Further research is also required to formalize safety constraints, ethical governance mechanisms, and clinical protocols to support responsible translational deployment.

By explicitly acknowledging these limitations, the present work aims to serve as a transparent foundation for interdisciplinary collaboration rather than a finalized clinical solution.

IX. CONCLUSION

This work presents an extended neuromorphic framework for brain–chip interfaces aimed at restoring motor and autonomic function through adaptive neural bypass mechanisms. By integrating spiking neural networks, closed-loop BCI architectures, and biologically informed design, the framework outlines a realistic pathway toward restorative neuroengineering.

Although significant challenges remain in hardware integration, biological compatibility, and ethical governance, the convergence of neuromorphic computing and BCIs provides a strong foundation for future experimental validation. The proposed architecture is intended to serve as a foundational reference for future experimental validation, hardware–software co-design, and translational research efforts. By articulating a neuromorphic closed-loop BCI framework grounded in neural engineering principles, this work aims to support the development of clinically viable neuroprosthetic systems and to inform ongoing research within the Journal of Neural Engineering community.

X. ACKNOWLEDGMENTS

The authors acknowledge institutional support and interdisciplinary discussions that contributed to this work.

A. Author Contributions

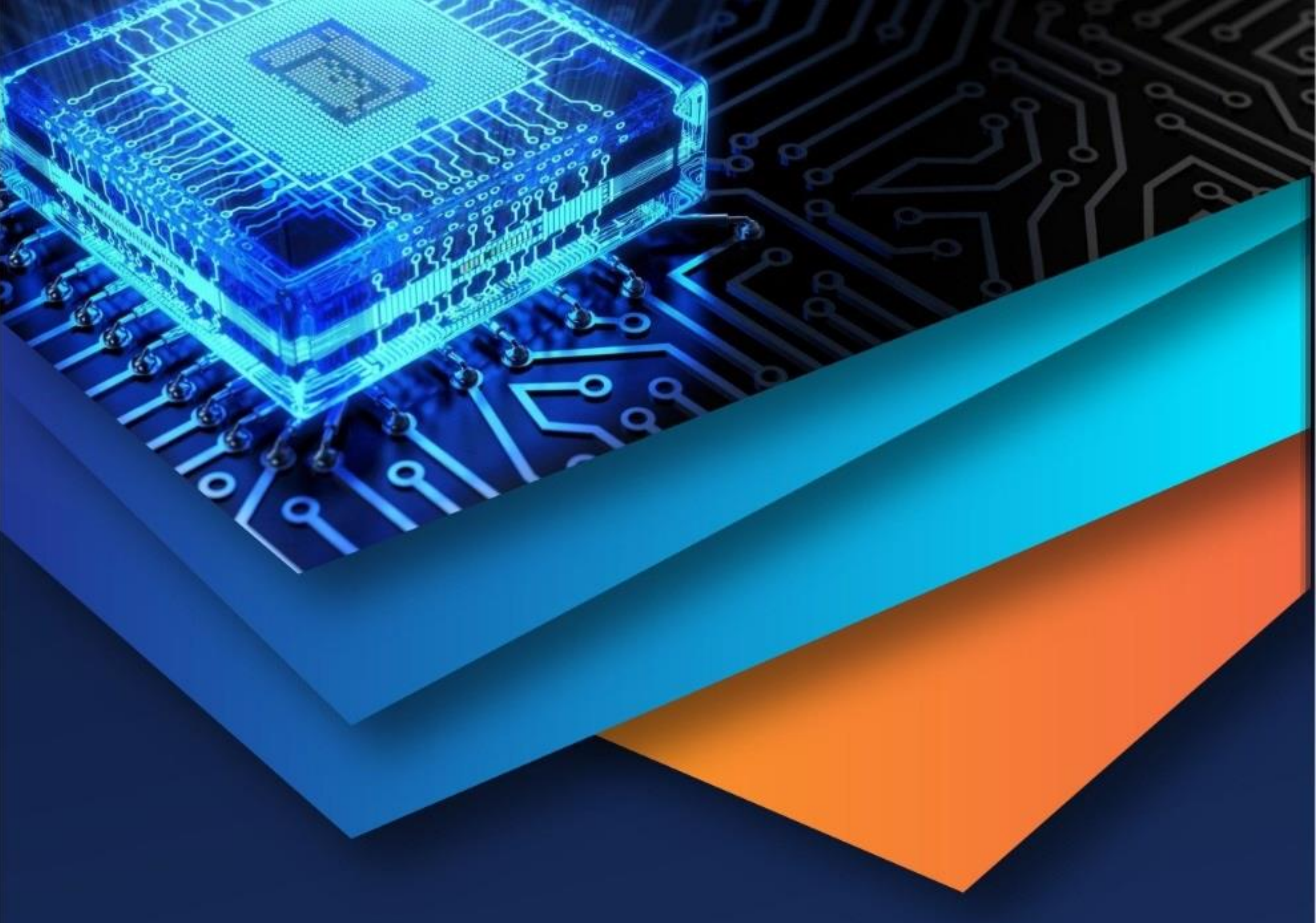
Anand Rawat and Anandi Singh: Conceptualization, system architecture, writing—original draft. Anamika Yadav and Anand sen: Literature analysis, ethical assessment, writing—review and editing. Ananya Agarwal: Simulation and formulation.

B. Data availability

No new experimental data were generated in this study.

REFERENCES

[1] Nicolelis M A L 2001 Actions from thoughts Nature 409 403–407
[2] Donoghue J P 2002 Connecting cortex to machines Nat Neurosci 5 1085–1088
[3] Hochberg L R et al. 2006 Neuronal ensemble control of prosthetic devices Nature 442 164–171
[4] Shenoy K V and Carmena J M 2014 Combining decoder design and neural adaptation in brain–machine interfaces Neuron 84 665–680
[5] Fetz E E 2007 Volitional control of neural activity Nat Rev Neurosci 8 418–428
[6] Jackson A, Mavoori J and Fetz E E 2006 Long-term motor cortex plasticity induced by an electronic neural implant Nature 444 56–60
[7] Lebedev M A and Nicolelis M A L 2006 Brain–machine interfaces Trends Cogn Sci 10 536–546
[8] Raspopovic S et al. 2014 Restoring natural sensory feedback in real-time bidirectional hand prostheses Sci Transl Med 6 222ra19
[9] Indiveri G et al. 2011 Neuromorphic silicon neuron circuits Front Neurosci 5 73
[10] Indiveri G and Liu S-C 2015 Memory and information processing in neuromorphic systems Proc IEEE 103 1379–1397
[11] Davies M et al. 2018 Loihi: A neuromorphic manycore processor with on-chip learning IEEE Micro 38 82–99
[12] Furber S B et al. 2014 The SpiNNaker project Proc IEEE 102 652–665
[13] Maass W 1997 Networks of spiking neurons Neural Comput 9 279–304
[14] Gerstner W and Kistler W 2002 Spiking neuron models Cambridge Univ Press
[15] Markram H et al. 2011 Spike-timing-dependent plasticity Front Synaptic Neurosci 3 4
[16] Mussa-Ivaldi F A and Miller L E 2011 Brain–machine interfaces J Neural Eng 8 025001
[17] Carmena J M 2013 Advances in neuroprosthetic learning J Neural Eng 10 050201
[18] Clausen J 2009 Man, machine and in between Nat Rev Neurosci 10 291–297
[19] Farina D et al. 2021 The extraction of neural information from the peripheral nervous system Nat Biomed Eng 5 1306–1318
[20] Rawat A and Yadav A 2025 The Neuromorphic Conductor Preprints.org doi:10.20944/preprints202511.1462.v1



10.22214/IJRASET

INDEX COPERNICUS 45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY