Neuro-INT Mamba: Architectural Principles

Neuro-INT Mamba Project

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1 Introduction

Neuro-INT Mamba is a bio-inspired architecture designed for dexterous manipulation. It integrates State Space Models (SSM) with key neurobiological principles to achieve real-time, adaptive, and multi-modal control.

2 Core Architectural Pillars

2.1 Dual-Stream Intrinsic Neural Timescales (INT)

The architecture implements parallel processing streams with different discretization steps (Δ):

- **Fast Stream (Sensory)**: Small Δ, simulating the Primary Sensory Cortex (S1/M1) for rapid response to high-frequency stimuli.
- **Slow Stream (Cognitive)**: Large Δ, simulating the Prefrontal Cortex for long-term integration and goal maintenance.

2.2 Predictive Coding & Efference Copy

Inspired by the brain's ability to predict sensory consequences of motor commands:

- Each layer generates a prediction of the next state.
- The network processes the *prediction error* ($x_{actual} - x_{predicted}$), significantly reducing redundancy and focusing on unexpected perturbations.

2.3 Chandelier Gating Mechanism

Mimics the inhibitory control of Chandelier cells (ChCs) on pyramidal neurons:

$$Gate(x) = x \cdot \sigma(\alpha - \beta \cdot \|x\|^2) \tag{1}$$

This mechanism prevents neural "over-firing" and ensures stability during high-intensity sensory input.

2.4 Spinal Reflex Loop

A low-level, fast feedback loop that operates in parallel with cortical processing. It provides immediate proportional-derivative-like corrections to maintain physical stability without requiring high-level cognitive overhead.

2.5 Thalamic Multi-modal Fusion

The Thalamic Encoder acts as a gateway, projecting diverse sensory modalities (proprioception, tactile, vision) into a unified latent space, enabling coherent cross-modal integration.

3 Real-time Simultaneous I/O

Unlike traditional Transformers that suffer from $O(L^2)$ or $O(L)$ inference latency, Neuro-INT Mamba leverages the recurrent form of SSMs to achieve $O(1)$ per-step inference, allowing for seamless input-output coupling in closed-loop robotic control.