Neuro-INT Mamba: Architectural Principles

Neuro-INT Mamba Project

December 18, 2025

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.
- **Intent Prior**: High-level intent (e.g., from EMG) acts as a prior to bias the prediction, enabling faster error correction during 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 implements a Proportional-Derivative (PD) control logic:

$$u_{reflex} = -(K_p \cdot \theta + K_d \cdot \dot{\theta}) \tag{2}$$

where θ and $\dot{\theta}$ represent joint positions and velocities. This mimics muscle spindle sensitivity. The gains K_p and K_d can be dynamically modulated by higher-level intent (e.g., EMG intensity) to adjust joint stiffness during contact.

2.5 Thalamic Multi-modal Fusion

The Thalamic Encoder acts as a gateway, projecting diverse sensory modalities into a unified latent space:

- **Tactile Spatial Prior**: Uses 1D Convolutional layers to capture spatial correlations in array-based tactile sensors.
- **High-Res Vision**: Optimized projection layers with LayerNorm for stable integration of high-dimensional visual features.
- **EMG Transfer Learning**: Integrates surface Electromyography (sEMG) signals to capture human motor intent.
- **Muscle Synergy Bottleneck**: Extracts low-dimensional control primitives (synergies) from high-dimensional intent, enabling human-like coordination.

This enables coherent cross-modal integration before cortical processing.

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.