

PhD Structure Plan

Proposed PhD Title/Direction

Toward Efficient Neuromorphic Tactile Processing: From Sensing to Active Efficient Coding

Research Goal

- Biological systems encode sensory input efficiently and sparsely through spikes.
 - Neuromorphic systems offer energy-efficient, event-driven computations.
- **Implement a tactile pathway for efficient information processing based on Efficient Coding Principles.**

Focus Areas

- Neuromorphic encoding of analog tactile signals into spikes.
- Extraction of perceptual features.
- High-level integration of information with control/adaptation mechanisms.

Overview of Research Stages

Stage	Focus	Outcome
Neuromorphic Tactile Transducer	Convert tactile analog signals to spikes (bio-inspired sensors)	Silicon chip + characterization
Tactile Processing Primitives	Extract motion & frequency features	Modular spike-based computation units
Higher-Order Perceptual Features	Texture, Slip, Shape, Contact, etc.	Learn invariant tactile representations
Efficient Coding Control	Adapt sensory encoding to task & energy efficiency	Active / Predictive coding architecture

First Stage: Neuromorphic Tactile Transducer

Key steps:

- Implement bio-inspired encoding from capacitive & piezoelectric sensors.
- Characterize fabricated chip (test setup under development).
- Record real tactile data (texture scanning experiments).

Second Stage: Tactile Processing Primitives

Goal: Design of the foundation of sensory features (motion and frequency).

Core primitives:

- ***Motion unit:*** Detects local/global motion motion direction and velocity.
- ***Frequency unit:*** Extracts temporal vibration patterns.

Outcomes: Basis set for a hierarchical, efficient tactile processing pathway.

→ Results in modular processing units producing basis features for integration in higher-level percepts.

Motion units

- Could be inspired by visual motion detection models (correlation, token-based methods) or dendritic computation.
- Two layers structure:
 - Local motion processing in motion unit receptive field (aggregated taxels).
 - Integration of local motions into global motion.
 - End-inhibition from extra-RF for edge detection.
- **Requirements:** Robust to noise and capable of identifying \neq temporal patterns.

Frequency units

Goal: Implementation of a neuromorphic PLL to extract input's frequency components.

- Bursting neurons are natural rhythmic oscillators.
- Learn parameters to lock into input frequency.
 - Robustness to noise/perturbation.
 - Ideally tunable bandwidth sensitivity.
- Frequency extraction independent from stimulus velocity.

Third Stage: Higher-Level Perceptual Features

Goal: Learn invariant tactile representation (for texture, shape, etc.).

- Makes use of combination, correlation or integration of the tactile primitives outputs spatially and temporally to extract more task-relevant features.
- Analog to how early visual features (edges, orientation, motion) lead to perception of shapes.

Fourth Stage: Efficient Coding Control Layer

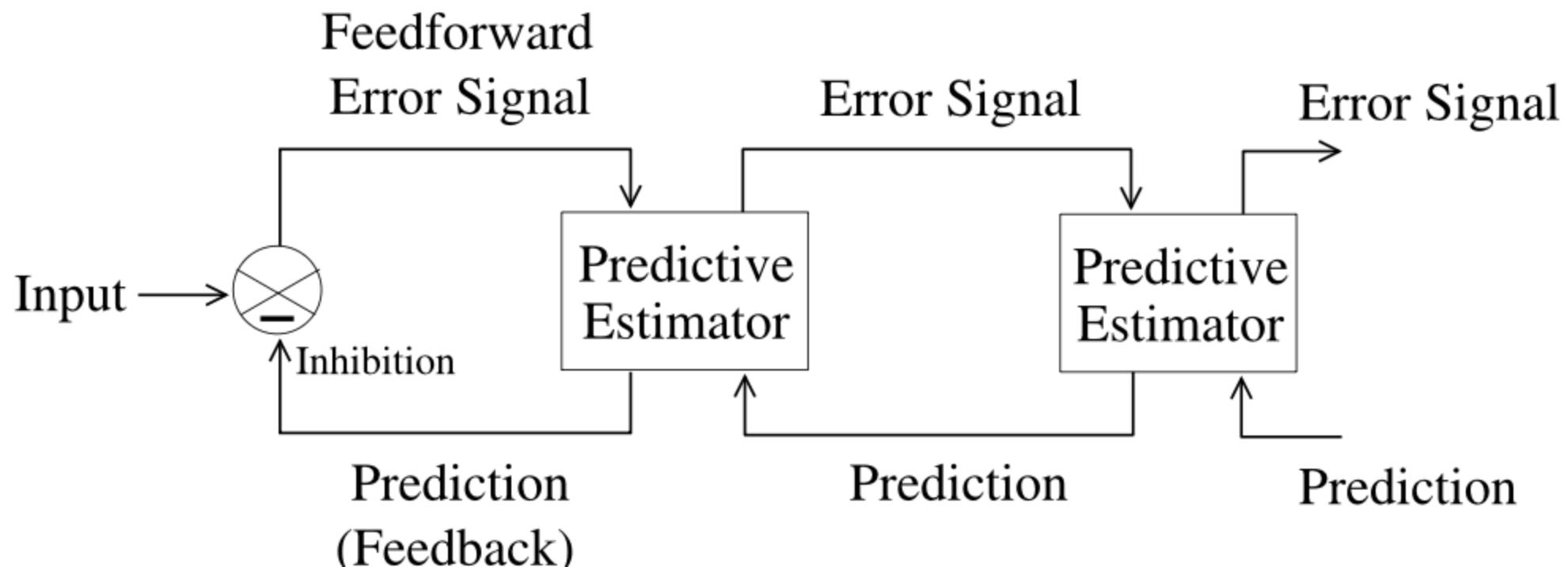
Goal: Design a control scheme optimizing both task performance and system energy efficiency.

Active Efficient Coding: Adapts biases/gains of lower layers via feedback using a Reinforcement Learning Framework.

Disadvantages: Large time invested required and not really neuromorphic with the traditional theory.

Predictive Coding

- Uses a hierarchical network minimizing prediction error.
- Feedforward = residual error / Feedback = prediction.
- Only unexpected information is propagated.

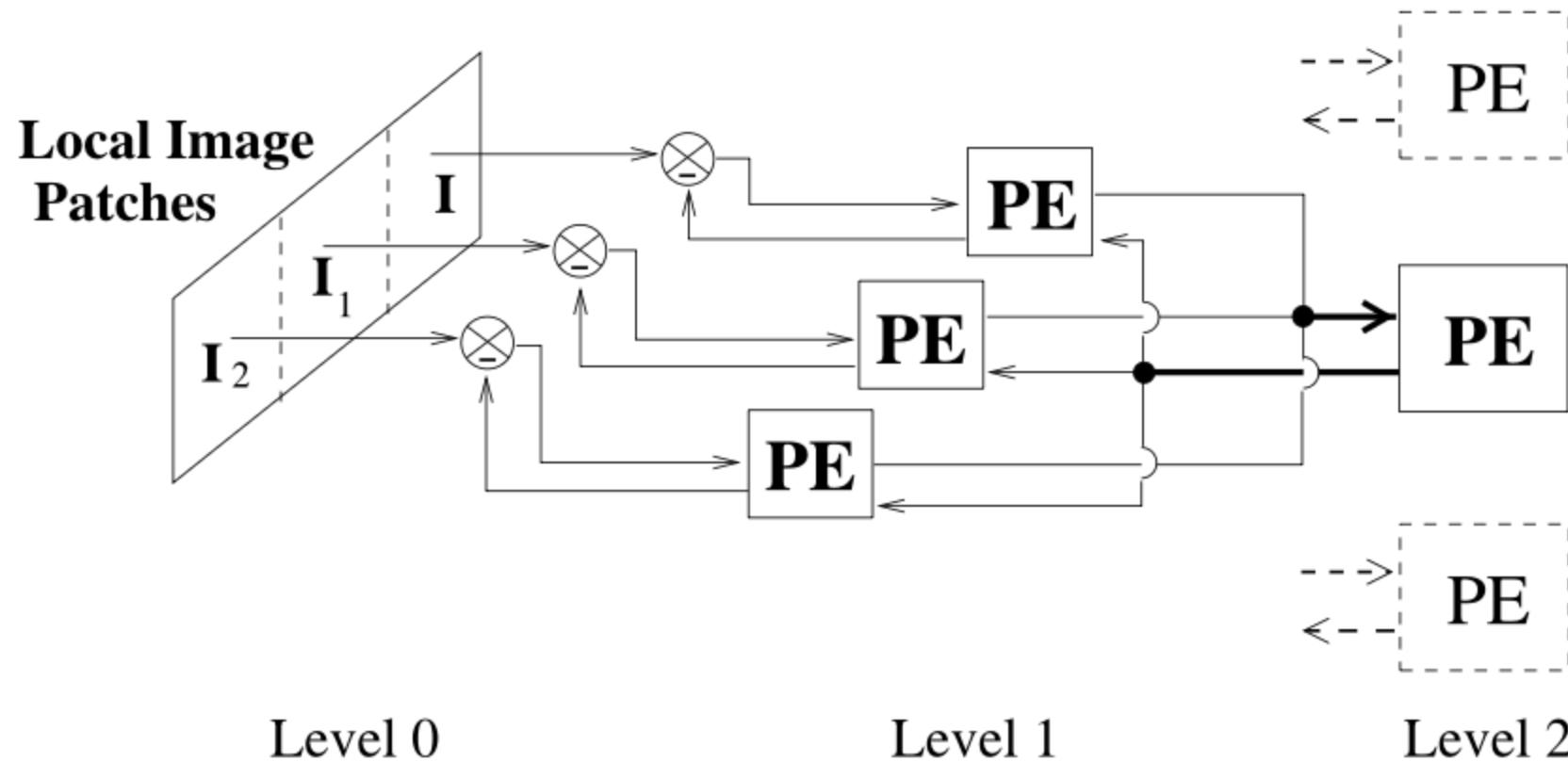


Tactile Pathway Overview

Hierarchy:

- **Bottom Layer:** Encode local dynamics (motion, frequency) using tactile primitives.
- **Intermediate Layers:** Learn invariant representations (texture, shape) by integrating local features.
- **Top Layers:** Use Predictive Coding to provide feedback to lower layers to modulate parameters/sensitivity based on task performance and efficiency.

Tactile Sensory Pathway Information Integration



Expected Contributions

- Bio-inspired tactile transducer with RAI / SAII mechanoreceptors.
- Tactile computation primitives for motion/frequency extraction.
- Adaptive control architecture based on Efficient Coding Principles.
- Tentative to model Tactile Sensory Pathway.

Proposed Timeline

Year	Focus	Outcome
Year 1	Neuromorphic Tactile Transducer Design/Simulation + Literature Review	Transducer Chip Design + Fab Submission
Year 2	Literature Review + Tactile Processing Primitives + Chip Characterization/Tactile Recordings	Motion + Frequency Neuromorphic Primitives, Tactile Dataset for texture (or other ?)
Year 3	Higher-Level Perceptual Features // Predictive Coding Framework	Basic Tactile Tasks implementation (Texture recognition, motion detection)
Year 4	Thesis + Remaining Points	