Embodied neuromodulation for neuromorphic rhythmic control

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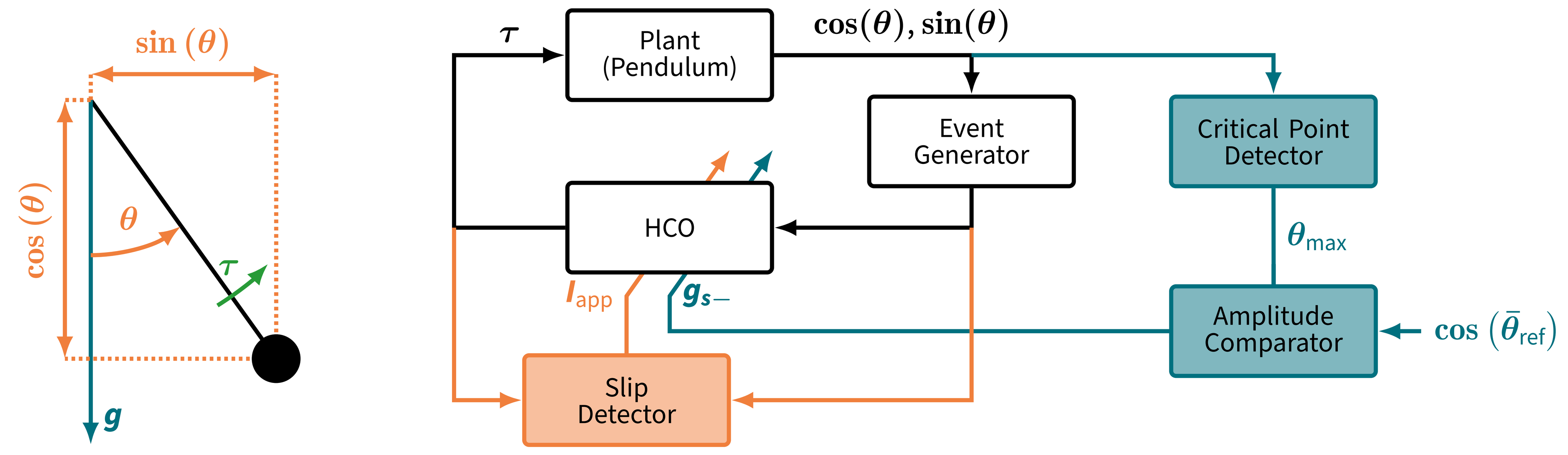
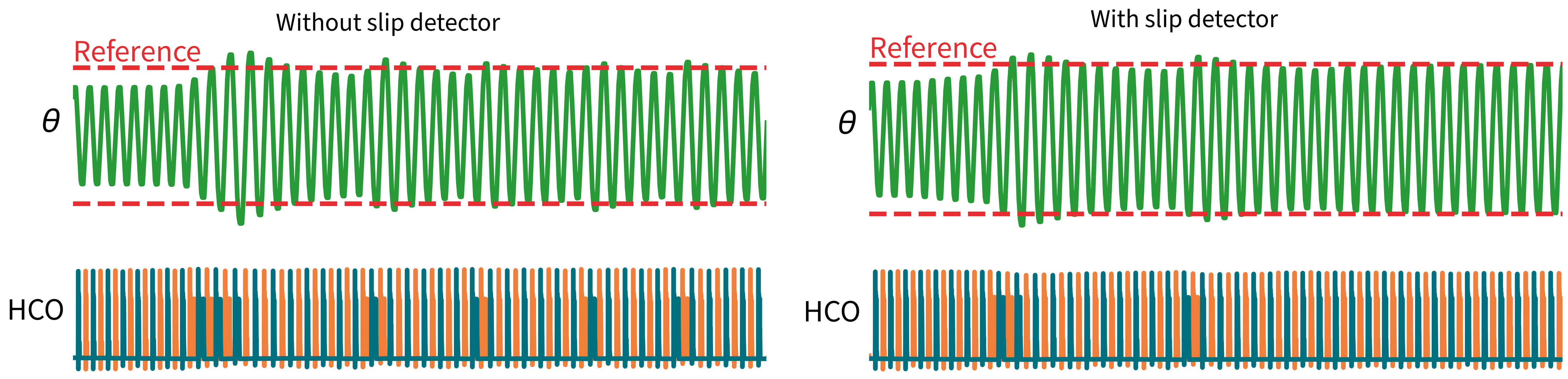
Neuromorphic control for a rhythmic system

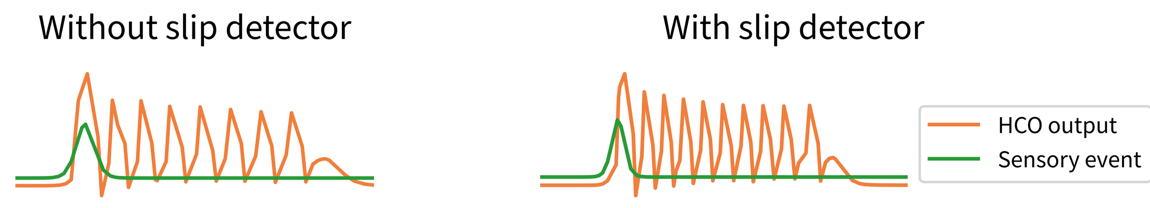
Motivation: Control of rhythmic systems is well suited for neuromorphic engineering due to the inherent rhythmic nature of neurons and the brain.
In this poster: Design of a neuromorphic control loop for a pendulum and implementation of critical blocks in CMOS technology.





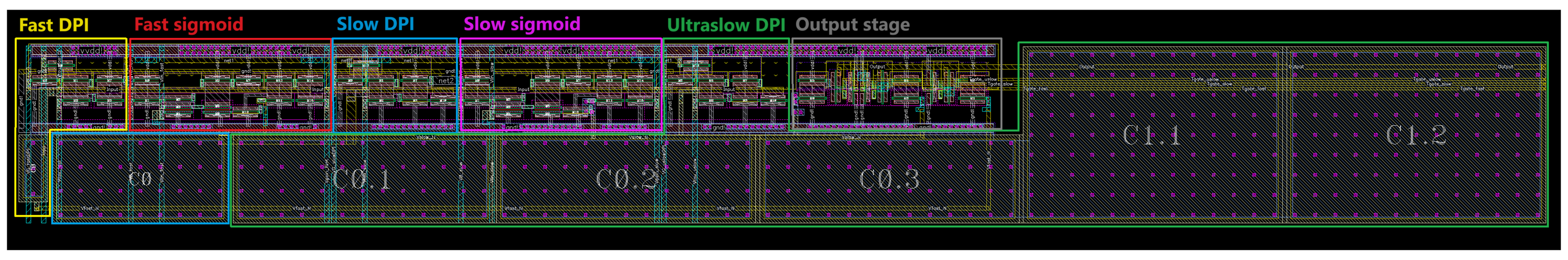
- Control of the pendulum is achieved by a **half-center oscillator (HCO)** nested inside **3 control loops**.
- The **direct sensory feedback loop** generates sensory events that synchronize the HCO with the physical system.
- The **amplitude control loop** detects the maximum amplitude and **modulates the burst width** to **change the injected torque** to reach a desired amplitude.
  → Requires detection of a maxima.
- The **frequency control loop** detects the slip between the HCO output and the sensory events and **modulates the HCO frequency** to match the physical system.
  → Requires detection of coincidences.

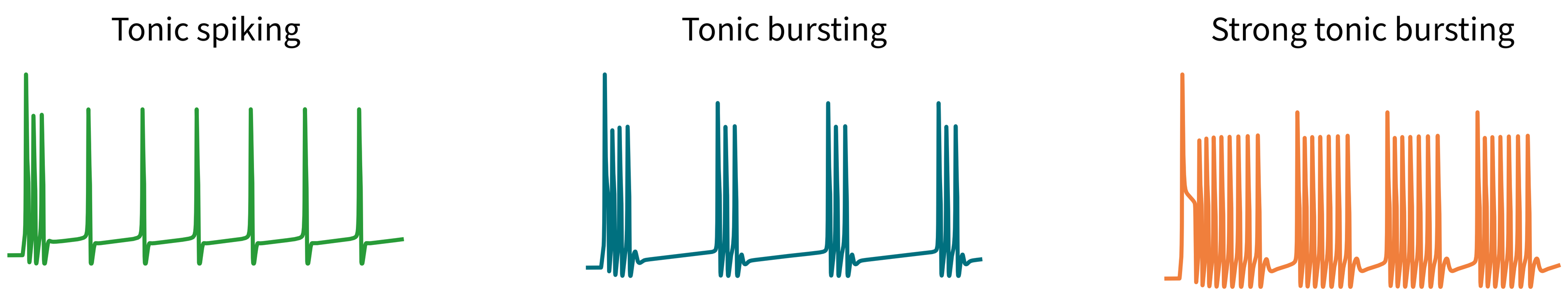
- The controller is able to sustain the pendulum oscillations by modulating two parameters of the HCO to achieve the desired amplitude and lock on to the natural frequency of the system.
- Without the slip detector, the HCO is too fast and doesn't synchronize with the sensory events, leading to continuous amplitude oscillations.



Neuromodulable CMOS neurons

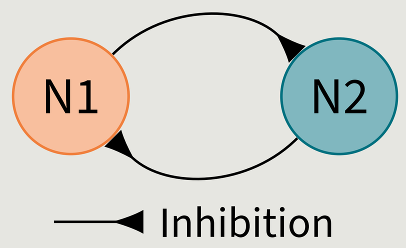
Analog CMOS current-mode neurons with **neuromodulation** capabilities *[Mendolia et al. 2023]*





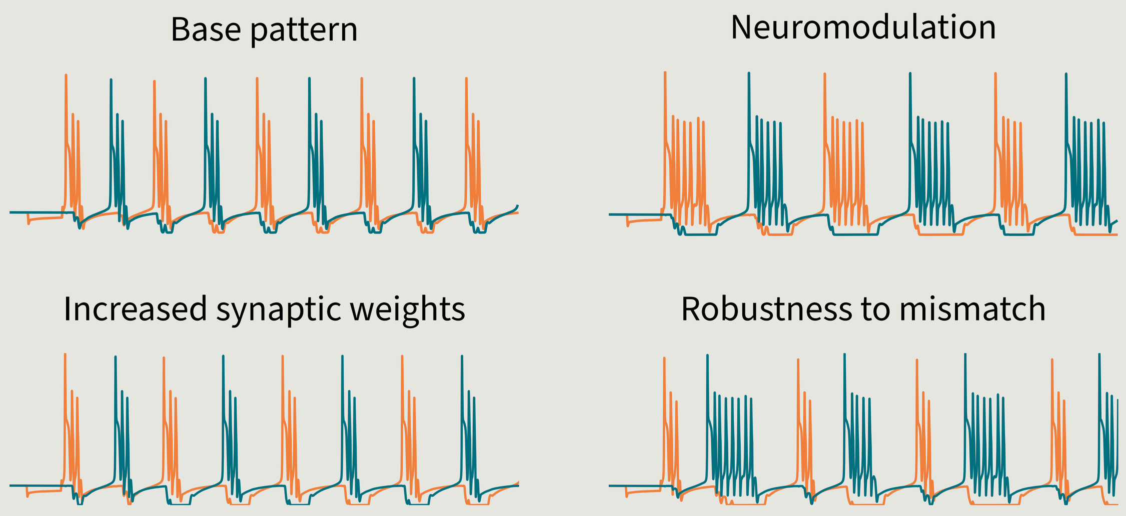
Neuromodulatory synapses can modulate the behavior of these neurons by regulating a **single bias voltage**.

Half-center oscillator



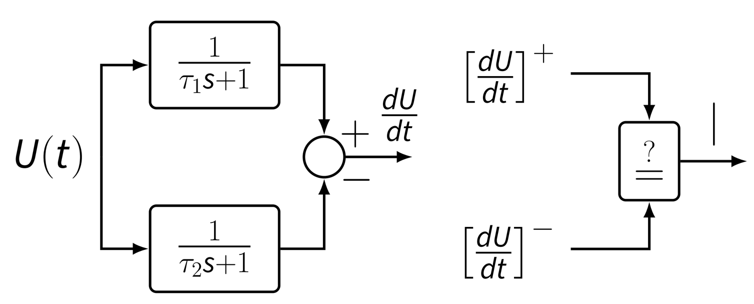
The HCO creates robust, self-sustaining, and **tunable** oscillations

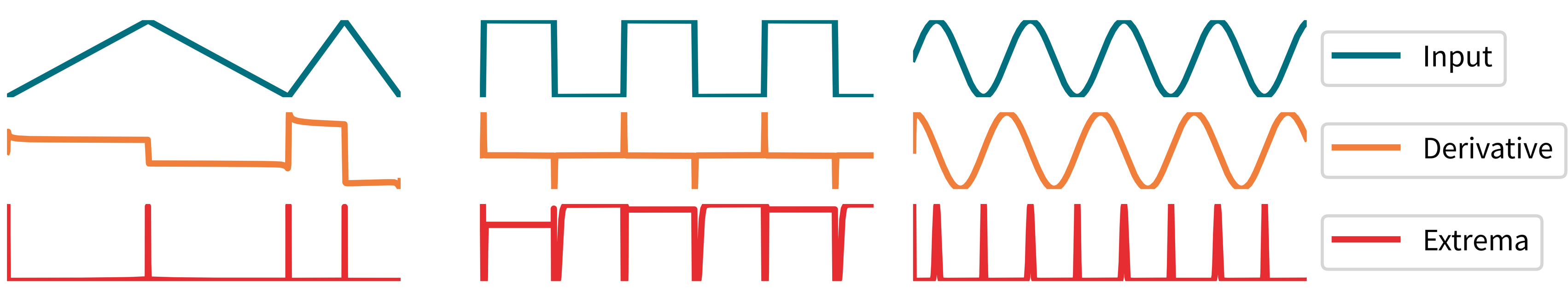
- Neuromodulation: signal strength and frequency tuning
- Synaptic weights: frequency tuning
- High robustness to neuron mismatch



Critical point detector

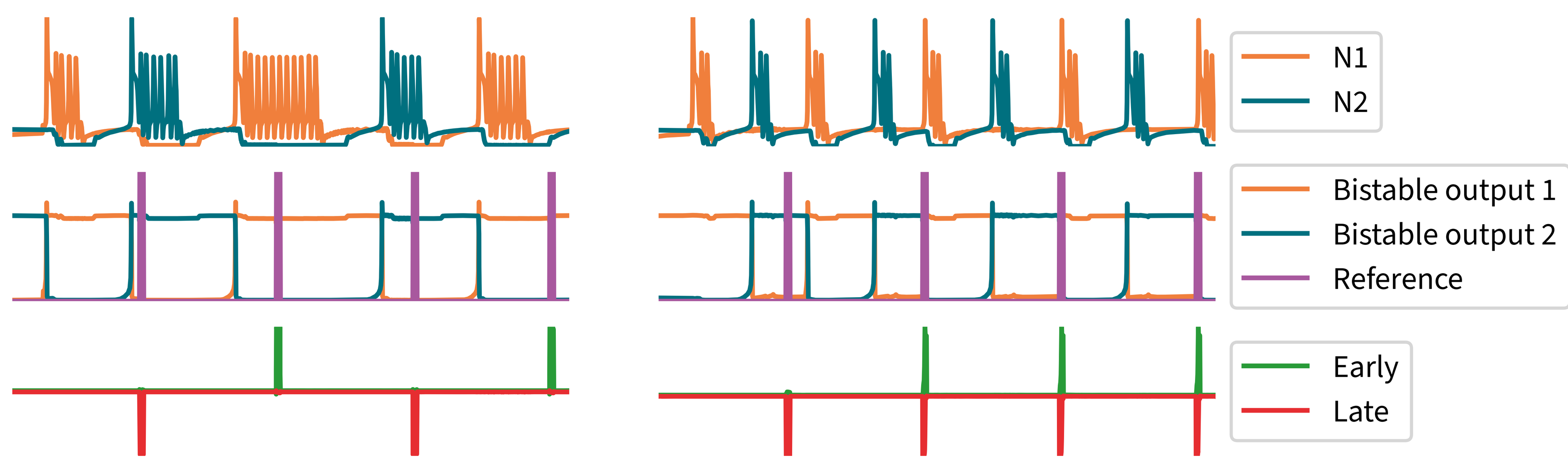
- Current-mode **low-pass filters** (differential pair integrators) with slightly different time constants
- **Connected substractively** to obtain a signal proportional to the **derivative** of the input signal
- Rectification and comparison with a bump circuit *[Delbruck 1991]* to detect maxima and minima





Phase slip detector

- Each HCO neuron triggers the switching of a current-mode **bistable** system
- The bistable outputs are multiplied by the reference signal using a CMOS current multiplier
- The resulting signal indicates whether the motor neuron is firing early or late, triggering the neuromodulation of the HCO
- When the reference coincides with the firing of the motor neuron, the two modulation signals cancel out



Conclusions

Our results demonstrate that **embodied neuromodulation** is a valuable alternative to traditional firing-rate/synaptic plasticity-based approaches for **designing adaptive neuromorphic controllers**, effective for **controlling rhythmic mechanical systems**, such as legged robots and prostheses.

Neuromorphic **central pattern generators** are ideal for generating and controlling actuation patterns thanks to their **robustness and tunability**. They integrate easily into **sensorimotor feedback loops** and can be paired with **neuromorphic signal processing** blocks to create energy-efficient agents.

We have demonstrated that the neuromorphic signal processing blocks theorized for the rhythmic pendulum control problem can be **implemented in analog CMOS technology** using known subthreshold circuits, paving the way for the design of fully **neuromorphic and ultra-low-power controllers**.

Future work

- Chip layout and experimental validation of simulations
- Exploration of practical applications in robotic actuation and active prosthetics

References

Delbruck, T. (1991). "'Bump' circuits for computing similarity and dissimilarity of analog voltages". In: IJCNN-91-Seattle International Joint Conference on Neural Networks. Vol. i, pp. 475–479.
Mendolia, Loris, Alessio Franci, et al. (Aug. 2023). "Networks of low-power CMOS neuromorphic neurons with robust neuromodulation capabilities". In: SCIoI & ISAB Summer School.

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