

Analog-electronic implementation of a harmonic oscillator recurrent neural network

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Brain-inspired oscillatory networks, such as the harmonic oscillator recurrent network (HORN, Fig. 1A), offer distinct advantages over non-oscillating architectures, including superior parameter efficiency, learning convergence, and robustness. However, translating these theoretical gains into energy-efficient analog-electronic hardware remains largely unexplored. To bridge this gap, we investigate the feasibility of realizing HORNs in analog-electronic circuitry while preserving the computational efficacy of their digital counterparts.

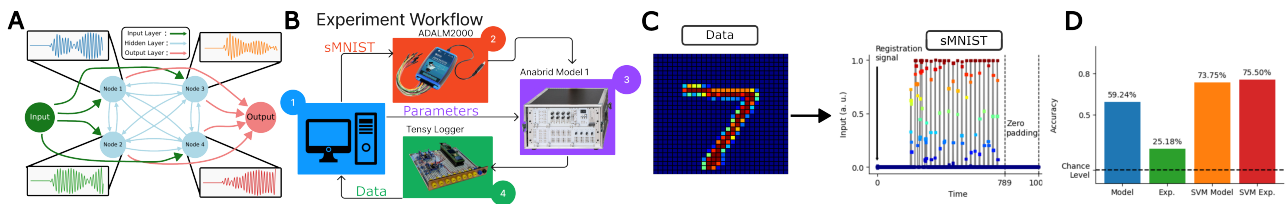


Figure 1: . Experimental setup and performance. (a) Experimental setup: digital computer (1), signal generator (2), analog computer (3), and data logger (4). (b) Four-node HORN model with example dynamics (inset plots). (c) MNIST data: original 28×28 pixel sample (left) and sMNIST version (right). (d) Classification accuracy of digital model (blue), analog with digital readout (green), digital with SVM readout (orange), and analog reservoir with SVM readout (red).

To do so, we employed a “digital-twin” approach to train an analog hardware-constrained, four-node HORN *in silico* via backpropagation through time (BPTT) for the sequential MNIST (sMNIST) task (Fig. 1C). These optimized parameters were then mapped onto a physical analog-electronic computer (anabrid Model-1, Fig. 1B). While the analog hardware faithfully replicated the digital model’s oscillatory dynamics, directly applying the digital affine readout yielded only 28.39% agreement in predictions against the analog implementation. Analysis revealed that, this failure underscores a fundamental precision mismatch, where the analog substrate cannot resolve the fine-grained decision volumes exploited by floating-point digital models. To prove the underlying information remained intact in the analog implementation, we adopted a reservoir computing strategy. By treating the analog system as a reservoir and retraining the linear readout on its physical outputs, classification performance was fully recovered. This approach achieved 75.50% accuracy, effectively matching and slightly exceeding the digital twin’s 59.24% (Fig. 1D) [2].

Taken together, this proof of concept establishes that analog-electronic circuits can efficiently leverage brain-inspired transient oscillatory dynamics for complex computation, offering a promising pathway for ultra-low-power neuromorphic architectures and energy-efficient edge-computing applications.

[1] F. Effenberger et al., Proc. Natl. Acad. Sci., 122(4), e2412830122, 2025.

[2] P. Carvalho et al., Phys. Rev. Applied, 24 (6), 064055, 2025.