Analog Gradient-Based In-Situ Learning with Liquid Memristor Devices for Neuromorphic Hardware

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Neuromorphic hardware based on memristors with liquid active layer [1] can be used to implement neural network with low power and limited area alongside harnessing the advantages of liquid devices such as low cost, simplicity, and large-scale fabrication. Here, we report the implementation of an artificial neural network (ANN) with an analog gradient-based in-situ training framework instead of relying on conventional approach of using analytical gradients or local plasticity rules. A hardware-in-the-loop training approach was implemented, where the intrinsic nonlinear I–V characteristics of the memristors were used as activation functions. Gradients required for backpropagation algorithm were directly obtained using an analog finite-difference method by biasing two identical devices at incrementally different voltages. This enables direct computation of dI/dV without explicit modeling. The gradient extraction method showed strong similarity with the numerical gradient by achieving a mean RMSE (Root Mean Square Error) of 8.38% and high reproducibility (mean R^2 of 0.98). Using the analog gradients and leveraging the non-linearity of I-V curves, ANN simulations in Python achieved a 94.67% validation accuracy on the iris dataset (5-fold Cross validation) using only two devices as neurons in a single hidden layer. This performance compares extremely well to software-based tanh activation (96%) and even outperforms ReLU activation (88.7%). Performance scalability was also demonstrated using the MNIST dataset in a two-hidden layer setup, for which a 96.2 % accuracy was achieved with the devices' experimental data as hidden neurons, compared with 96.8% accuracy with tanh activation. These results validate the effectiveness of the analog finite-difference based gradient extraction method and highlight the potential of liquid memristor-based systems for energy-efficient neuromorphic computing.

[1] A. V. Silva et al., Nano Lett., 25(25), 9944–9951, 2025.