Fabrication of Memristive Reservoir Computing Devices for Control Applications

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Developing control systems based on alternative device physics has the potential to significantly reduce power consumption, structure complexity, and device size compared to those of traditional control systems. Such advancements are key to enabling advancing increasingly sophisticated robotic vehicles and miniature mobile robots. Memristive devices have emerged as a promising technology, creating new opportunities for constructing neural network devices dedicated to neuromorphic computing applications.[1-3] At the same time, further advancements in nanofabrication and device-oriented work are needed to explore new hardware solutions for control applications.

We report a nanoelectronics-enabled analog control system that emulates the dynamic response behaviors of conventional controllers for real-time robotic control applications while significantly reducing training costs, power consumption, and the overall system footprint.

This innovative system features a hardware-based reservoir computing (RC) network consisting of interconnected memristive channels made from layered semiconductor structures, which exhibit nonlinear memristive and short-term memory characteristics (Fig. 1). By mapping the kinetic states of the robotic system to high-dimensional reservoir state space, this system generates expected motor control signals with minimal reliance on software/firmware implementation and analog-to-digital signal conversion, thereby significantly improving the control system's energy and resource efficiency of the control system.

In this work, we implemented this RC-based control system in a motor-driven lever-balancing test (Fig. 2). Initially, the control task was performed using a digital PID controller to generate training data for the RC network's readout layer (Fig. 2a). The collected PID control data were then used to train the presented RC network, which was subsequently used to demonstrate its control functionality (Fig. 2b). Figure 3 presents the time-dependent lever angle data obtained from both control systems. This result reveals that the RC-based control system can balance the lever in a dynamic manner very similar to the PID controller from which the RC system learned the dynamic response characteristics. More importantly, in comparison to traditional PID control systems, our RC-based system demonstrates similar control behavior while operating with three orders of magnitude lower power consumption for processing sensory signals (~10 μW).

This work could be further developed to construct ultralow-power edge computing and control systems for a wide range of miniature robotic applications.

[1]Yoo, S., Chae, S., Chiang, T. et al. Efficient data processing using tunable entropy-stabilized oxide memristors. Nat Electron 7, 466–474 (2024). https://doi.org/10.1038/s41928-024-01169-1

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[2]Huang, Y., Ando, T., Sebastian, A. et al. Memristor-based hardware accelerators for artificial intelligence. Nat Rev Electr Eng 1, 286–299 (2024). https://doi.org/10.1038/s44287-024-00037-6

[3]Buyun Chen, Hao Yang, Boxiang Song, Deming Meng, Xiaodong Yan, Yuanrui Li, Yunxiang Wang, Pan Hu, Tse-Hsien Ou, Mark Barnell, Qing Wu, Han Wang, and Wei Wu. A memristor-based hybrid analog-digital computing platform for mobile robotics. Science Robotics. https://www.science.org/doi/full/10.1126/scirobotics.abb6938

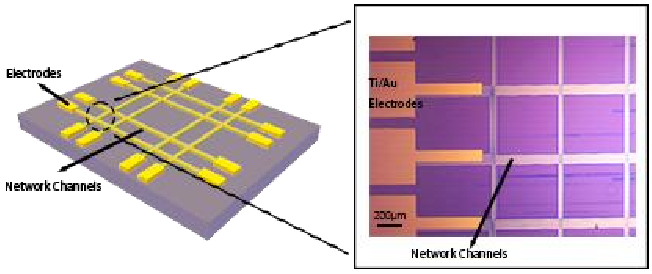

Figure 1 Schematic illustration of the Bi2Se3 reservoir layout and the zoomed-in OM of the electrodes deposited on the dendrites of the network.

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Figure 2 Photo of the testing rig for the motor-driven lever balancing test. (a) PID control test. (b) RC control test.

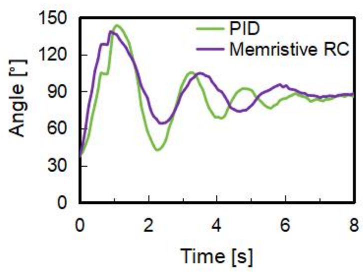

Figure 3 The time-sequential lever angle signals were measured from the control tests for both PID control and memristive RC.

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