SCIENCE CHINA
Information Sciences

• LETTER •

April 2026, Vol. 69, Iss. 4, 149201:1–149201:2
https://doi.org/10.1007/s11432-024-4693-3

A bio-inspired tactile-olfactory fusion perception system based on a memristive spiking neural network

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Received 10 August 2024/Revised 30 January 2025/Accepted 15 October 2025/Published online 15 January 2026

Citation Yang C, Wang X P, Chen Z F, et al. A bio-inspired tactile-olfactory fusion perception system based on a memristive spiking neural network. Sci China Inf Sci, 2026, 69(4): 149201, https://doi.org/10.1007/s11432-024-4693-3

Star-nosed moles can accurately sense objects in complete darkness through their unique nose (Figure 1(a)), where 22 fleshy, movable appendages fan out around the nostril [1]. The appendages have mass Eimer's organs, which act as the tactile receptors and can detect objects in stiffness, hardness, and topology. This unique structure can simultaneously capture the identifiable information of the touching object, including smell, stiffness, and topology. This captured tactile and olfactory information is then coded in spikes and projected to subsequent brain areas for feature extraction, information fusion, and object recognition. These facts inspired Liu et al. [2] to develop a humanoid hand with an artificial neural network (ANN) to achieve human identification in challenging rescue environments. However, their work employed a traditional ANN for object recognition, which is not conducive to integrating spatiotemporal information. Also, the calculations are performed in a non-neuromorphic system where storage and computation units are separated, resulting in high energy consumption.

Spiking neural networks (SNNs) are considered more bio-plausible and energy-efficient than traditional ANNs because they compute using discrete spikes and can integrate information from both temporal and spatial dimensions [3]. Memristors are known as ideal devices that mimic synapses due to their excellent characteristics, including two terminals, nanoscale dimensions, and adjustable resistance. However, there is still a lack of systems that employ memristors to reduce the computing consumption of SNNs and achieve object recognition using tactile and olfactory information, especially those deployed on hardware.

This work proposes a bio-inspired tactile-olfactory fusion perception system based on a developed humanoid hand and an on-chip deployed memristive SNN, achieving brain-like parallel IMC and information integration. As shown in Figure 1(b), the proposed system consists of a developed humanoid hand [2] that mimics the nose structure of the star-nosed mole and a memristive SNN that aims for object recognition with a more bionic computing manner. The humanoid hand integrates 14 force sensors on each fingertip and six gas sensors into the palm, which can capture the tactile and olfactory information of the grasping object concurrently with high resolution and rapid response (Appendix A). The memristive SNN is implemented by deploying a bio-inspired SNN on an HfO_x [4] memristor-based digital-analog hybrid computing platform. The platform uses a dual-core ARM (Acorn RISC Machine) Cortex-A9 processor as the core controller to schedule all calculations of SNN, such as data preparation, convolutional and fully connected layer computation with memristor-based processing element (MPE) (Appendix B), and neuron state updates. The data preparation mainly includes preprocessing and rearrangement. The data preprocessing involves a normalization to mitigate data variability, random sampling recombination to generate more grasp gestures, and 4-bit quantization to facilitate calculation with the MPE (Appendix C). The data rearrangement changes the arrangement of samples or feature maps to facilitate MPE parallel computing.

The bio-inspired SNN (Figure 1(c)) consists of four convolutional layers (denoted as TConv1, TConv2, OConv1, and OConv2) and two fully connected layers (denoted as FC1 and FC2) that mimic the functions of primary areas of the star-nosed mole for feature extraction, the association area for multi-modal fusion, and the multi-sensory neuron area for object recognition. Considering the precision of the memristive weight and the trade-off between computational accuracy and cost, 4-bit weights and integrate-and-fire (IF) neurons are used in the SNN (Appendix D).

To help the SNN better adapt to the variability and limited precision of memristor weights, a certain intensity of random noise [4] and a quantization-aware training method (Appendix E) are utilized during the offline training phase. Considering the trade-off

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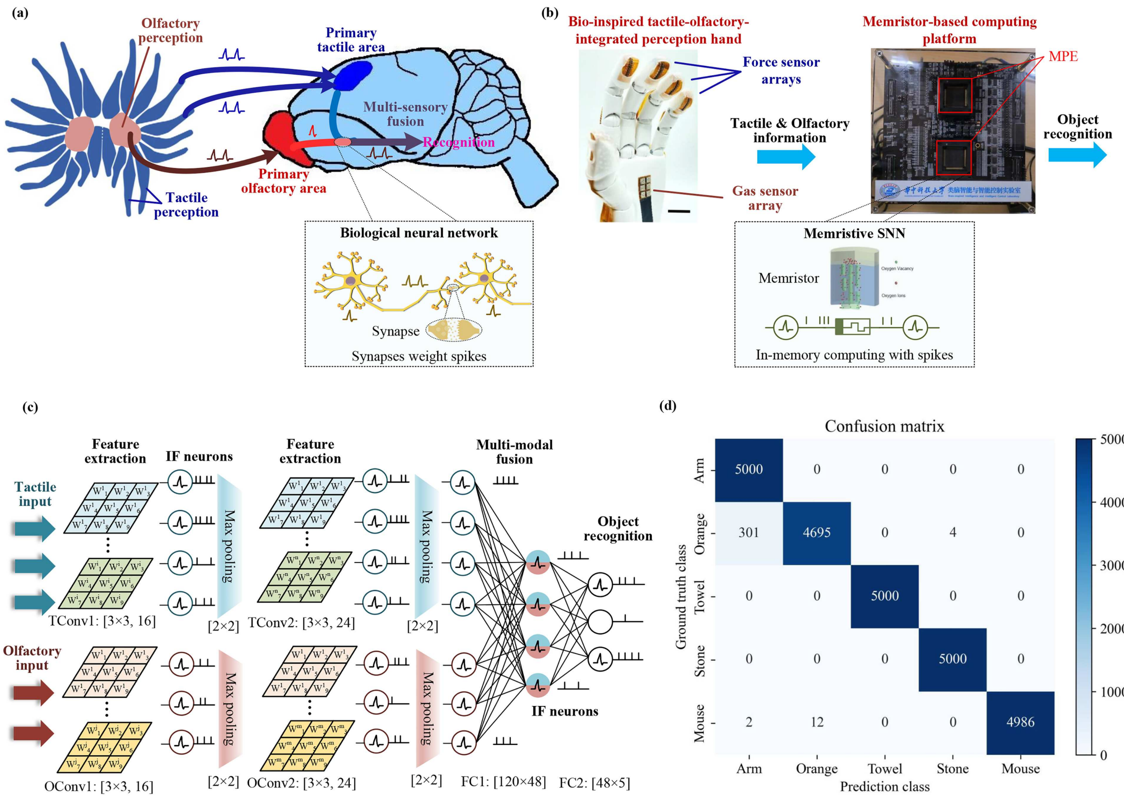

Figure 1 (Color online) (a) Schematic illustration of the bio-sensory perceptual system in the star-nosed mole. (b) The proposed bio-inspired perception system based on the memristive SNN. (c) Diagram of the designed SNN. (d) Recognition confusion matrix with 4 time steps. The final recognition accuracy is 98.72%.

of accuracy and latency, the rate coding with 4 time steps is employed. The model achieves the best performance at epoch 12, where the best training and test accuracy are 100% and 99.84%, respectively. The best test accuracy is better than that considering only tactile (98.7%) or olfactory (91.74%) information, indicating that integrating multi-modal information is conducive to recognition.

During the deployment phase, the weights of the trained SNN are first converted into signed 4-bit integers to match the memristive precision, then mapped on the memristor array in a certain order, and finally programmed as the conductance of memristors through a write-verify method [4]. To perform parallel IMC with the memristor array, the data rearrangement that includes unfolding and random filling needs to be performed (Appendix F).

Considering the weight mapping offset (Figure F1(c)) and the resolution of the ADC is related to the integration time, a layer-by-layer fitting strategy is adopted to reduce the calculation errors and their accumulation. Moreover, to avoid additional computation arising from fitting, we proposed a method that integrates the fitting coefficients into the IF neuron model to reconstruct different neurons for each layer (Appendix G). Thanks to the spatiotemporal information integration of SNN, the final on-chip recognition accuracy achieves 98.72% in the human detection task (Figure 1(d)), with an accuracy loss of 1.12% caused by deployment, which is still higher than the accuracy of 97.8% reported in the previous work [5]. The energy consumption is 0.72 μJ/sample, which is reduced by 94.50% compared to a typical digital acceleration system (Appendix H).

Conclusion. In this work, we implement a bionic tactile-olfactory fusion perception system based on an on-chip deployed memristive SNN. The system achieves higher recognition accuracy and lower energy consumption since it considers brain-like parallel IMC and spatiotemporal information integration. To this end, we customize a memristor-based computing platform, design a bio-inspired SNN, and present effective training and deployment methods to alleviate the negative impacts of memristor non-idealities on accuracy. On this basis, we propose reconstructing different IF neurons for each layer to prevent additional fitting calculations caused by result correction. Such an energy-efficient object perception system has promising applications in non-visual and resource-constrained rescue scenarios.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 62236005, 62566004, 61936004).

Supporting information Appendixes A–I. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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