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PAICar: a prototype of an embodied neuromorphic intelligent robot platform

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Embodied neuromorphic intelligence (ENI) [1,2] integrates neuromorphic computing with embodied perception-action loops, simulating the brain's operational principles. It equips agents with perception, decision-making, and action capabilities, leveraging brain-inspired architectures for efficient and flexible computation. ENI emphasizes multimodal sensory integration and interaction with environments through motor systems. At its core, neuromorphic computing utilizes a spiking neural network (SNN) to process information in a manner similar to biological brains. Moreover, neuromorphic chips replicate neural structures, offering low power consumption and high parallelism, enabling real-time decision-making in dynamic environments and driving the evolution of robotic intelligence.

However, ENI is still in its early stages and faces numerous practical challenges, including limitations in accuracy, computational efficiency, robustness, and environmental adaptability. For example, while robots based on the DYNAP-SE2, BiCoSS, Loihi, Rolls, TrueNorth, and Tianjic platforms have demonstrated progress in tasks such as attitude estimation, sensor fusion, obstacle avoidance, and speech recognition, the capabilities of current neuromorphic hardware remain largely confined to relatively simple models. Neuromorphic learning algorithms also exhibit limitations in adaptability and generalization, hindering fully embodied intelligence [3]. Furthermore, multimodal integration and collaborative processing remain challenging, as current SNN models are often single-modality focused, lacking a complete SNN-based multimodal framework [4]. High-level decision-making for complex tasks such as navigation or human-robot interaction is also limited.

To overcome these challenges and advance ENI toward real-world robotic autonomy, we present PAICar, a multimodal, energy-efficient ENI robotic platform built on PAICORE [5], a thousand-core neuromorphic chip supporting large-scale parallel SNN computation. PAICar is capable of accommodating diverse scenarios and dynamic external environments. It supports multiple neural encoding schemes and various SNN models, enabling collaborative computation across multimodal SNN networks. Based on this platform, we developed a brain-inspired autonomous localization and tracking robot, which integrates multiple SNN modules to perform real-time tasks including sound source localization and tracking, object recognition, obstacle avoidance, and decision-making in real-world scenarios. PAICar is an ENI prototype robot that provides strong support for the development of ENI technologies and is expected to further promote advancements in both research and practical applications of ENI.

PAICar robot platform. PAICar integrates multimodal sensing—including sound, RGB-D vision, and thermal infrared—with event-driven SNN processing deployed on the PAICORE neuromorphic processor. The system supports real-time spatiotemporal feature extraction, modality fusion, and embodied action. As shown in Figure 1(a), sensor inputs are encoded into spikes and processed by multiple SNN modules. A neural state machine (NSM) performs decision-level fusion and coordinates task transitions, including sound localization, target tracking, obstacle avoidance, and path planning. Built upon these components, PAICar realizes a neuromorphic embodied robot capable of performing localization and tracking tasks, as illustrated in Figure 1(b), which shows the robot operating in various indoor and outdoor scenarios.

Sound-based localization. As part of the ENI loop, PAICar employs a sound-based localization module in which auditory signals from a four-channel microphone array are converted into spike representations and processed by a compact fully connected SNN for direction-of-arrival estimation. To ensure robustness under real-world auditory conditions, where noise interference is common, we enhanced the training data by introducing a diverse set of monophonic noise types across multiple signal-to-noise ratios (SNRs). This noise-augmented training strategy exposes the model to realistic acoustic variations and strengthens the generalization capability of the sound localization module. This augmentation ex-

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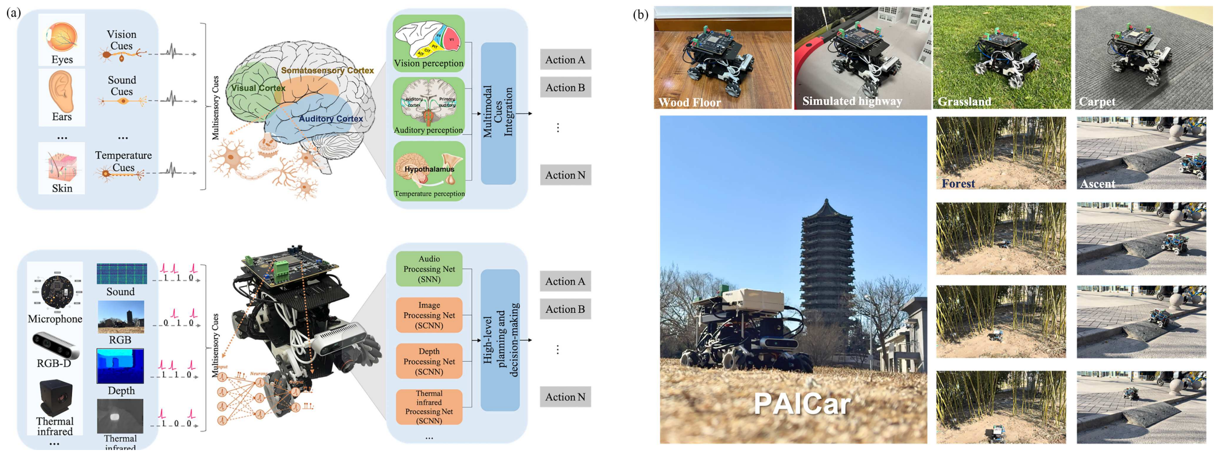

Figure 1 (Color online) (a) Overview of PAICar and its multimodal neuromorphic perception-decision-action loop; (b) PAICar in different indoor and outdoor scenarios.

poses the SNN model to diverse acoustic conditions, enabling the auditory module to maintain stable neural dynamics and reliable localization within the embodied neuromorphic framework.

Thermal imaging-based target detection. A two-stage target detection algorithm based on multi-patch localization is employed to achieve thermal imaging-based target detection. This approach effectively addresses the challenge in current studies where SNNs require a large number of timesteps in object detection tasks due to the need to compute precise bounding box coordinates. Traditional SNN-based object detection algorithms often incur high computational costs when regressing bounding boxes, limiting their practicality in real-time applications.

Depth-based obstacle avoidance module. The depth-based obstacle avoidance module provides fast, reliable environmental assessment essential for safe embodied operation. Depth maps from the D435i camera are preprocessed into low-dimensional spike representations, enabling rapid inference through a lightweight three-layer SCNN. The network categorizes scenes into four avoidance actions—turn-left, turn-right, stay-still, or turn-around—allowing PAICar to respond immediately to hazards. This event-driven design minimizes computational overhead while ensuring real-time reactivity in dynamic environments, making depth-guided avoidance an integral component of PAICar's ENI perception-action loop.

RGBD-based path planning. To complement local sensing and enhance robustness under complex conditions, PAICar incorporates an RGB-D based high-level planning module that integrates global and local spatial information. Top-down depth maps and RGB imagery are fused to construct a scene representation supporting global path planning via the reinforcement-learning-based BrainQN algorithm, while local planning adjusts trajectories based on real-time sensory feedback. This dual-level strategy enables PAICar to navigate efficiently, maintain target tracking, and adapt to changing environments. As part of the ENI framework, this module links multimodal perception to long-horizon action selection within a unified spiking-based decision architecture.

Conclusion. PAICar serves as a prototype for an ENI robot platform, demonstrating how multimodal sensing, spiking computation, and neuromorphic decision dynamics can be integrated into a unified, biologically inspired perception-action loop. The proposed system incorporates a novel architecture that supports multiple SNN models in parallel, enabling the execution of complex tasks such as sound source localization, thermal imaging-based target detection, obstacle avoidance, and path planning with high accuracy and robustness. As shown in the extensive experiments detailed in the supplementary materials, PAICar not only enhances computational efficiency but also significantly improves environmental adaptability and task generalization. Beyond technical advancements, PAICar serves as a validation prototype for ENI, pushing the boundaries of brain-inspired robotics. By closely mimicking biological perception-action loops and leveraging neuromorphic computing paradigms, PAICar lays the foundation for the next generation of intelligent robots capable of real-time learning, adaptation, and autonomous decision-making in complex, unstructured environments. This research marks a step forward in realizing truly ENI, driving the evolution of robotics towards systems that can operate with the cognitive flexibility and efficiency of biological organisms.

Supporting information Videos and other supplemental documents. 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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