BIOMIMETICS

The multifaceted approach to embodied intelligence in robotics

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Embodied intelligence refers to the aspects of sensory-motor behavior that reside in the body, relying on its mechanical properties and physical interactions with the environment (*1*). Here, motor control is not entirely managed by the computing system—whether it is the nervous system of an animal or the controller of a robot. Instead, motor behavior is partially shaped mechanically by external forces acting on the body. Nature offers numerous examples of embodied intelligence that have been inspiring robotics for years. When we walk, our compliant knees can compensate for small changes in terrain mechanically, with no involvement of the central nervous system. When we grasp an object, our fingers adapt to its shape mechanically, without controlling the movement of each phalanx.

One of the key contributions of embodied intelligence to robotics is that it simplifies control by offloading some of the control tasks to the body itself and its interaction with the environment. In complex robotic systems, equipped with many actuators and sensors, control tasks require sophisticated information processing and related computation capacity and energy. In the embodied intelligence framework, motor behaviors emerge naturally from the robot's physical engagement with its surroundings, reducing the need for detailed, centralized control, whose complexity may introduce computational burden and hamper effectiveness. Embodied intelligence and soft robotics (*2*) are deeply intertwined, given that the deformability of soft body structures plays a crucial role in generating emergent behaviors through interaction with the environment. The recent progress of soft robotics technologies is enabling more opportunities for the investigation and the implementation of embodied intelligence.

This special issue discusses diverse interpretations of embodied intelligence—from the use of physical interactions in robot control to purely mechanical functions obtained from instabilities of soft materials and stimuli-responsive materials. The issue also reports original implementations of embodied intelligence in robotics, showing emergent behaviors with reduced control. Such implementations are presented in two Research Articles. The paper by Gilday *et al.* focuses on the embodied intelligence of robotic hands in manipulation tasks and proposes a study with more than 56 design parameters, inspired by the diversity of grasping organs in the present and past animal kingdom. The authors show how to capture emergent behaviors in diverse hand morphologies and implement them in robots. The paper by Yue *et al.* puts embodied intelligence in the context of a hierarchical organization of control, as inspired by the octopus, which integrates sensorized suckers, decentralized embodied computation in the arm, and centralized control in the brain. The paper reports the integration of suction cups into fluidic-driven soft circuits that exploit their fluidic energy and information capacity to capture key aspects of embodied intelligence.

Two Focus papers provide further perspectives on embodied intelligence. Aucone and Mintchev discuss the contribution of embodied intelligence to aerial robots, proposing an approach that makes use of passive interactions to achieve robust and effective behavior in the wild. Milana *et al.* discuss how embodied intelligence is the key element of purely mechanical robots that exploit the intrinsic properties of soft materials, such as instabilities, to achieve movement through mechanical means, without the need for electronics or complex control systems. The Review by Chen *et al.* goes to the level of the material itself, analyzing the use of stimuli-responsive materials to obtain autonomous behavior on the basis of physical intelligence.

The special issue contributes to understanding how the diverse demonstration of embodied intelligence can be beneficial in various contexts in the field of robotics. By leveraging physical interactions, material properties, and decentralized control mechanisms, the authors showcase more efficient and effective behaviors for new generations of robots operating in the real world. As soft robotics and smart materials continue to evolve, further technological tools will become readily available to implement embodied intelligence for a diverse range of use cases. In the future, a transition is envisioned from the existing principles to a more structured method for modelling and implementing embodied intelligence in robotics.

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