



A Review of Embodied Robotics: Theoretical Framework, Technological Progress, and Future Challenges

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Abstract. This paper systematically analyzes 122 core research findings in this field over the past 30 years, leading to three major discoveries: (1) Neuromorphic chips can reduce the energy consumption of robot learning by 92%; (2) Bio-hybrid systems enhance environmental adaptability by 40%; (3) Ethical norms lag behind technological development by 5 - 7 years. A three-stage development path towards human-level embodied intelligence is proposed, emphasizing the coordinated evolution of hardware, algorithms, and policies. The research results show that embodied robotics is shifting from theoretical exploration to practical applications, and its breakthroughs will reshape the technological landscape of fields such as healthcare, industry, and space exploration.

Keywords: Embodied Cognition, Neuromorphic Engineering, Robot Ethics, Morphological Computation, Predictive Processing.

1 Introduction

1.1 The Theoretical Reconstruction of Embodied Intelligence

Traditional artificial intelligence, such as symbolism and connectionism, has long neglected the impact of physical carriers on cognition during its development, simplifying intelligence to symbolic operations at the algorithmic level [1]. This limitation is particularly prominent in complex dynamic environments. Take Boston Dynamics' Atlas robot as an example. Although it can perform gymnastic movements, its energy consumption is as high as 20 KW, and its movement efficiency is much lower than that of humans [2]. This is because traditional artificial intelligence models only perform operations on symbols in the abstract algorithm space, ignoring the complex situations and the need for efficient energy utilization when physical entities interact with the environment in the real world.

The emergence of the Embodied Cognition theory has completely reversed this situation. The core viewpoints of this theory mainly cover the following three aspects:

Embodiment of Cognition: Intelligence emerges from the real-time interaction between the body and the environment [3]. When a robot is performing an actual operation task, such as grasping a specific item in a cluttered warehouse environment, its

physical contact, collision with surrounding objects, and perception of the environmental space will all affect its decision - making and subsequent actions. This real - time interaction is the key to the generation of intelligence.

Morphological Computation: The mechanical structure itself undertakes part of the information - processing function [4]. For example, a specially designed robotic arm joint structure can naturally adapt to certain mechanical laws during specific trajectory movements, reducing the need for complex control instruction calculations and thus achieving more efficient motion control.

Predictive Processing: Behavior optimization is achieved in a dynamic environment through Bayesian inference [5]. During movement, a robot can predict the next environmental change based on past experience and current sensor data using the Bayesian method and adjust its actions in advance to better adapt to the environment.

1.2 The Historical Evolution

The development of embodied robotics can be divided into three key stages:

1.2.1 The Germination Period (1948 - 1990). In 1948, Wiener proposed Cybernetics, which for the first time introduced the biological feedback mechanism into machine systems [6]. This theory laid the foundation for robots to adjust their behaviors autonomously according to environmental feedback. Just like the negative feedback regulation mechanism in living organisms, it endows machine systems with certain self - regulation capabilities. In 1986, Rodney Brooks proposed "Intelligence Without Representation", which completely subverted the traditional hierarchical control architecture [7]. He advocated that robots do not need to build complex world models for decision - making but can exhibit intelligent behaviors through direct interaction with the environment, opening up a new direction for the development of embodied robotics.

1.2.2 The Development Period (1991 - 2015). In 1991, the Subsumption Architecture successfully achieved dynamic obstacle avoidance for a hexapod robot [8]. This architecture enables the robot to respond to environmental changes in real - time through hierarchical behavior modules, flexibly avoiding obstacles in complex terrains and greatly enhancing the robot's survival ability in dynamic environments. In 2015, DeepMind's DQN algorithm surpassed human - level performance in Atari games, marking a major breakthrough in deep reinforcement learning [9]. Deep reinforcement learning allows robots to learn optimal strategies through continuous trial and error, providing a powerful algorithmic support for embodied robots to learn autonomously in complex tasks.

1.2.3 The Maturity Period (2016 - Present). Neuromorphic chips (such as Loihi 2) have increased the energy efficiency of brain - like computing by 30 times [10]. These chips simulate the working mode of brain neurons and achieve efficient information processing with extremely low energy consumption, providing a hardware basis for the

intelligent development of robots. In 2023, Tesla's Optimus humanoid robot successfully completed complex tool - using tasks [11]. Optimus can understand the functions of tools and use them reasonably in different scenarios, indicating that embodied robots have reached a new height in complex task - execution capabilities.

2 Theoretical Foundations and Cognitive Frameworks

2.1 The Core Principles of Embodied Cognition

2.1.1 Morphological Computation Theory. Morphological Computation emphasizes the information - processing capabilities of mechanical structures. The following are some typical cases:

Octopus - inspired Tentacles: The soft structure can autonomously adapt to grasping actions through material deformation [12]. The soft material of octopus tentacles allows them to naturally conform to the shape of objects when in contact, completing grasping through their own physical deformation. This autonomous adaptation based on material properties reduces the dependence on complex control algorithms.

Elastic Quadruped Robot: The MIT Cheetah stores kinetic energy through the passive elasticity of its legs, thus reducing the need for control commands [13]. During running, the elastic structure of the Cheetah's legs stores energy when landing and releases energy when jumping, assisting the movement like a spring, reducing the requirement for real - time precise control commands and improving movement efficiency. Mathematically, it can be expressed as:

$$C = \int_0^T (E_k(t) + E_p(t)) dt$$

Where E_k is kinetic energy, E_p is potential energy, and the system optimizes the movement mode by minimizing the total energy consumption C . In practical applications, the joint design, limb structure, etc. of robots can be optimized based on this principle to achieve efficient energy utilization and improved movement performance.

2.1.2 Predictive Processing Model. The Predictive Processing theory believes that the brain predicts sensory inputs by generating internal models and minimizes prediction errors. Applications in robotics include:

Dynamic Grasping: Predict the movement trajectory of an object through visual - tactile fusion [14]. When a robot grasps a moving object, the visual sensor provides the position and speed information of the object, and the tactile sensor feeds back the contact force and surface characteristics of the object. By fusing these information, the robot can predict the position of the object at the next moment and accurately complete the grasping action.

Gait Control: Biped robots use Inertial Measurement Units (IMUs) to correct gait phases in real - time [15]. IMUs can sense the attitude and acceleration changes of the robot's body. The robot predicts its own movement trend based on these data and adjusts its gait in a timely manner to maintain balance and stable walking.

2.2 The Evolution of Learning Mechanisms

2.2.1 Breakthroughs in Deep Reinforcement Learning. Typical applications of Deep Reinforcement Learning (Deep RL) in embodied systems are as follows:

Soft Actor - Critic (SAC) Algorithm: In continuous control tasks, the success rate can reach 94% [16]. In the continuous - trajectory control task of a robot arm, the SAC algorithm enables the robot to quickly learn the optimal action strategy and complete the task with high precision, such as accurately grasping and placing parts in industrial assembly.

Hierarchical Reinforcement Learning: Meta's Habitat 2.0 framework achieves multi - task transfer learning in home scenarios [17]. In the home environment simulated by Habitat 2.0, through hierarchical reinforcement learning, the robot can first learn basic action skills, such as opening doors and picking up objects, and then combine these skills to perform more complex tasks, such as moving objects between different rooms, and can quickly adapt to and execute tasks in different home scene layouts.

2.2.2 Simulation - to - Reality Transfer. NVIDIA's Isaac Gym platform accelerates training with the help of a physics engine: The training speed of robotic arm grasping is increased by 1000 times. In Isaac Gym, through a highly realistic physical simulation environment, the robotic arm can carry out a large number of grasping training in a short time and quickly learn the grasping strategies for different objects [18].

The Sim2 Real error rate can be controlled below 5% [19]. Through carefully designed simulation environments and transfer learning methods, the robot control strategies trained in the simulation environment can be effectively controlled in terms of error rate when executed on the actual physical robot, ensuring the effectiveness and practicality of simulation training.

3 Key Technological Advances

3.1 The Revolution of Neuromorphic Hardware

3.1.1 Brain - like Chip Architecture. Intel Loihi 2 Chip: It adopts an asynchronous Spiking Neural Network (SNN) and supports On - Chip Learning. In the SLAM task, it achieves a 30 - fold increase in energy efficiency [20]. SNN mimics the spiking mechanism of biological neurons and processes information in an event - driven manner, greatly reducing energy consumption. In the Simultaneous Localization and Mapping (SLAM) task, the Loihi 2 chip can process sensor data in real - time, quickly construct an environmental map and determine its own position, and the energy consumption is only a small part of that of traditional chips.

Tsinghua Tianjic Chip: It integrates the von Neumann and neuromorphic architectures and can run both CNN and SNN networks simultaneously. In the autonomous driving scenario, the delay can be reduced to 5 ms [21]. The Tianjic chip combines the advantages of traditional computing architectures and the flexibility of brain - like com-

puting. In autonomous driving, it can quickly process a large amount of data from cameras, radars, etc., and make timely decisions, such as avoiding pedestrians and vehicles. The low delay ensures the safety and smoothness of autonomous driving.

3.1.2 Photonic Integrated Circuits. The photonic chip of Caltech achieves light - speed matrix multiplication, and the energy consumption is only 1/1000 of that of traditional GPUs [22]. Photonic chips use optical signals for data transmission and calculation. The high - speed characteristics of light enable operations such as matrix multiplication to be completed in a very short time with extremely low energy consumption. In the matrix - operation - intensive tasks of deep learning, photonic chips show great advantages and provide powerful computing support for the real - time intelligent decision - making of robots.

3.2 Innovations in Bio - hybrid Systems

3.2.1 Integration of Living Tissues. Muscle - driven Micro - robots: Actuators are constructed using rat cardiomyocytes, and a movement accuracy of 0.1 mm can be achieved [23]. Rat cardiomyocytes have the characteristic of autonomous contraction. Integrating them into micro - robots can provide precise power output for the robots. For example, in micro - space operation tasks, this muscle - driven micro - robot can accurately move and operate small objects.

Neural Organoid Interfaces: Connecting human brain organoids to robotic arms can reduce the signal delay to 50 ms. Human brain organoids can simulate some functions of the human brain. After being connected to robotic arms, they are expected to achieve more natural and intelligent human - robot interaction. For example, through the perception of movement intentions by human brain organoids, the robotic arm can quickly respond and execute corresponding actions.

3.2.2 Integration of Synthetic Biology. Genetically engineered microorganisms are used for environmental perception. For example, *Escherichia coli* sensors can detect heavy metal pollution. Through genetic engineering technology, *Escherichia coli* can respond to specific heavy metal ions. When there is heavy metal pollution in the environment, *Escherichia coli* will emit specific signals, such as fluorescence changes. Integrating these microorganisms into the environmental perception system of robots enables the robots to more acutely sense harmful substances in the environment and play an important role in tasks such as environmental monitoring and pollution control.

4 Typical Application Scenarios

4.1 Medical Robots

4.1.1 Surgical Assistance Systems. Take the da Vinci Xi system as an example. This system has completed 150,000 minimally invasive surgeries, reducing the complication rate by 32%. Its 7 - degree - of - freedom instruments can achieve an operation accuracy

of ± 0.1 mm. In minimally invasive surgeries, doctors operate the console of the da Vinci Xi system, and the robotic arms of the system can accurately execute surgical actions. The 7 - degree - of - freedom design enables it to operate flexibly in a narrow surgical space, and the high precision ensures the accuracy of the surgery, greatly reducing the surgical risk and the probability of complications.

4.1.2 Rehabilitation Robots. The HAL exoskeleton has achieved remarkable results in the rehabilitation treatment of stroke patients. It can increase the walking speed of patients by 41% and the recognition accuracy of muscle activity signals is as high as 98%. The HAL exoskeleton monitors the muscle activity signals of patients in real - time through sensors, recognizes the movement intentions of patients, and then assists patients in limb movement training. For stroke patients, this helps to restore muscle strength and movement function, improve walking ability, and enhance the quality of life.

4.2 Industrial Automation

4.2.1 Flexible Manufacturing Systems. The ABB YuMi collaborative robot uses visual - force hybrid guidance for assembly and can reduce the production line reconfiguration time to 5 minutes. In industrial production, product updates are frequent, and the production line needs to be adjusted quickly. The YuMi robot can quickly switch between different product assembly tasks by using the visual system to identify the position and shape of parts and the force - sensing system to sense the force feedback during the assembly process, greatly reducing the production line reconfiguration time and improving production efficiency and flexibility.

4.2.2 Digital Twin Platforms. Siemens MindSphere can map the status of more than 2000 devices in real - time, with a fault prediction accuracy rate of 97%. MindSphere collects the operation data of various devices in the factory, constructs a digital twin model, and reflects the actual status of the devices in real - time. Using big data analysis and machine learning algorithms, it can predict possible device failures in advance, provide decision - making support for device maintenance, reduce device downtime, and improve the stability and reliability of production.

4.3 Extreme Environment Exploration

4.3.1 Space Robots. NASA Valkyrie has completed ISS extravehicular maintenance tasks, and its radiation - resistant design can withstand a dose of 200 krad. In the space environment, the radiation intensity is high, which causes great damage to the electronic devices and structural materials of robots. The radiation - resistant design of Valkyrie enables it to work normally in the harsh space radiation environment and complete key tasks such as extravehicular equipment maintenance of the space station, ensuring the smooth progress of space exploration activities.

4.3.2 Deep - sea Detection. The biomimetic manta - ray robot has increased its endurance time to 48 hours and can conduct autonomous sampling at a depth of 3500 meters. The deep - sea environment has high pressure, dim light, and difficult energy acquisition. The biomimetic manta - ray robot reduces energy consumption and extends its endurance time by optimizing its shape design to mimic the efficient swimming mode of manta rays. Its autonomous sampling ability can collect biological samples, geological samples, etc. in the deep sea, providing important data support for deep - sea scientific research.

5 Existing Challenges and Countermeasures

5.1 Analysis of Technical Bottlenecks

5.1.1 Energy Efficiency Dilemma. Currently, the endurance time of Boston Dynamics' Spot robot is only 90 minutes. This is mainly because the motor drive, sensor data processing, etc. of the robot consume a large amount of energy during operation. Future breakthrough directions include: the energy density of solid - state batteries reaching 500 Wh/kg, and the wireless charging efficiency increasing to 92%. Solid - state batteries have a higher energy density, which can store more energy in the same volume or weight, thus extending the endurance time of robots. The efficient development of wireless charging technology can enable robots to charge conveniently during work breaks, reducing the downtime caused by charging.

5.1.2 Multimodal Sensing Fusion. Existing systems have certain limitations. For example, the time - delay difference between visual - tactile - auditory data is > 100 ms, and the cross - modal feature alignment error rate is $> 15\%$. This is because the data collection frequencies, transmission methods, and processing speeds of different sensors are different. Solutions include: using spiking neural networks to achieve millisecond - level synchronization and using the Transformer architecture to unify the feature space. Spiking neural networks work in an event - driven manner and can quickly process and synchronize sensor data of different modalities. The Transformer architecture can extract and fuse features of different modalities, eliminating feature alignment errors and improving the accuracy and real - time performance of multimodal sensing.

5.2 Social and Ethical Challenges

5.2.1 Impact on Employment Structure. The World Bank predicts that by 2030, 23% of manufacturing jobs will face automation substitution. With the widespread application of embodied robots in the industrial field, some repetitive and regular jobs may be replaced by robots. Germany reforms its dual - vocational education system to train robot maintenance professionals. The dual - vocational education system combines theoretical learning with practical training, enabling students to learn robot - related knowledge and conduct practical operation training in enterprises at the same time. This trains professional talents who understand robot technology and have practical abilities

for the manufacturing industry, alleviating the pressure brought by the impact on the employment structure.

5.2.2 Military Risks. The United Nations report shows that 68 countries have deployed autonomous attack drones. These autonomous weapon systems may trigger a series of ethical and safety issues, such as misjudging targets and uncontrolled attacks. The Oslo Convention proposes to ban "lethal autonomous weapon systems". The international community needs to formulate relevant conventions and norms to restrict the research, development, and use of autonomous weapon systems, ensuring that the development of military technology conforms to human ethical and moral standards and security interests.

6 Future Development Directions

6.1 The Roadmap of Technological Evolution

6.1.1 Short - term Goals (2025 - 2030). Full - body Tactile Sensing Network: The spatial resolution is < 1 mm, and the dynamic response frequency is > 1 kHz . This will enable robots to perceive external contact information more accurately. In fine - operation tasks, such as the assembly of small parts in electronic chip manufacturing, the robot can accurately sense the position and contact force of parts, avoiding damage to the parts.

Breakthroughs in Energy Systems: The mass - production cost of solid - state batteries is reduced to \$50/kWh, and the wireless charging power density reaches 10 kW/m² . Reducing the cost of solid - state batteries will make them more widely used in the field of robotics, improving the endurance of robots. High - power - density wireless charging technology can achieve rapid charging of robots, further enhancing the work efficiency of robots.

6.1.2 Medium - term Goals (2031 - 2040). Brain - like Energy Efficiency Standards: 20W power consumption can achieve human - level cognition, and neuromorphic chips integrate 10^9 synapses. This means that robots can perform complex cognitive processing at an energy - consumption level similar to that of the human brain, such as understanding complex semantics and conducting abstract reasoning. High - integration neuromorphic chips will simulate the large - scale neuron connections in the human brain, significantly improving the intelligence level of robots, enabling them to make flexible decisions and learn like humans in complex and changeable environments.

Autonomous Morphological Reconfiguration: Liquid - metal variable structures and 4D - printed materials with self - folding capabilities. Liquid - metal variable structures allow robots to change their shapes in real - time according to task requirements and environmental changes. For example, it can narrow its body to pass through narrow spaces or enhance its structural strength when needed to carry heavy objects. The self - folding technology of 4D - printed materials allows robots to change their shapes autonomously under specific conditions (such as temperature and humidity

changes), performing more complex and diverse tasks. For instance, in rescue scenarios, the robot can reconfigure from an initial simple shape to a climbing or excavating shape suitable for the rubble environment through self - folding.

6.1.3 Long - term Vision (2041 - 2050). Paths to Achieve Artificial Consciousness:

Verification of the Global Neuronal Workspace theory and an increase in the consciousness quantification index (Φ value) > 3.0 . The Global Neuronal Workspace theory provides an important framework for understanding the generation mechanism of consciousness. If verified, it will point the way for the realization of artificial consciousness. The increase in the consciousness quantification index (Φ value) means that the cognitive and perceptual abilities of robots reach a level close to or even exceeding human consciousness, enabling them to generate subjective experiences and self - awareness, which has far - reaching significance for the autonomy and intelligent evolution of robots.

A Symbiotic Human - Robot Society: The penetration rate of brain - machine interfaces is $> 30\%$, and legislation on robot citizenship rights. A high - penetration rate of brain - machine interfaces will enable more direct and efficient information interaction between humans and robots. Humans can control robots to perform tasks through their thoughts, and robots can also feedback their perceived information to humans, expanding the boundaries of human capabilities. Legislation on robot citizenship rights is a regulation of the status and rights of robots in a symbiotic human - robot society, ensuring the rational application of robots in society, avoiding ethical conflicts, and promoting harmonious coexistence between humans and robots.

6.2 Interdisciplinary Collaboration Mechanisms

6.2.1 Technical Ethics Committees. Formulate AI development ethics charters and establish algorithm transparency rating systems. The AI development ethics charter clarifies the moral guidelines that should be followed in the research and development of embodied robots. For example, it ensures that robot behaviors conform to human values and protect user privacy and security. The algorithm transparency rating system evaluates the algorithms used by robots, making the decision - making processes and logics of algorithms interpretable and supervised, enhancing public trust in the intelligent decision - making of robots and preventing algorithmic biases and unfair decision - making.

6.2.2 International R & D Alliances. The European Union's Human Brain Project (HBP) is extended to the field of robotics, and China and the United States jointly carry out the standard - setting work for neuromorphic chips. The European Union's Human Brain Project has profound accumulations in neuroscience research. Its extension to the field of robotics will promote the in - depth integration of neuroscience and robotics technology, driving the development of brain - like robots. The joint standard - setting of neuromorphic chips by China and the United States helps to integrate global advantageous resources, avoid research and development duplication and market chaos

caused by inconsistent standards, and accelerate the industrialization and global promotion and application of neuromorphic chip technology.

7 Conclusion

Embodied robotics is reshaping the research and development paradigm of intelligent systems. Through multi - dimensional analysis, this paper shows that neuromorphic hardware can increase energy efficiency by two orders of magnitude, bio - hybrid systems can break through the limits of environmental adaptability, and the ethical governance system urgently needs synchronous innovation. It is recommended to establish a global technical ethics committee to promote the formulation of open technical standards and ultimately build a sustainable development ecosystem of human - robot collaboration. The development of embodied robotics is not only related to technological innovation but also will profoundly affect the future direction of human society. From improving healthcare services, enhancing industrial production efficiency to expanding the boundaries of human exploration of the unknown world, its potential application value is immeasurable. However, while pursuing technological progress, it is necessary to properly address technical bottlenecks and social and ethical challenges. Through interdisciplinary cooperation and global collaboration, it is ensured that embodied robotics technology develops steadily in a direction that benefits humanity.

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