



Application of Robotics Technology in Extreme Environments

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Abstract. Extreme environment robots can replace humans working in dangerous scenarios such as the deep sea, space and nuclear industry, but their applications face many challenges. Technically, it needs to have extreme environmental adaptability, stable communication and autonomous decision-making ability. Key performance involves ontology structure, environmental perception, etc. At present, there are problems such as effectiveness and security. Research trends include bionic design, deep learning, materials that need to adapt to extreme environments and lightweight, energy involves nuclear batteries, perceptual navigation relies on special sensors and no GPS technology, and communication uses low latency technology. Typical applications include space and deep-sea exploration, nuclear industry processing, polar research and disaster relief. This paper summarizes its development history, key technologies, application fields and prospects, and provides a theoretical innovation path for the future by building a new framework. This project aims to promote the intelligent and practical development of robots in extreme environments.

Keywords: Extreme Environment, Robot, Intelligent Technology.

1 Introduction

With the deepening of a new round of scientific and technological revolution and industrial revolution, the demand for robots in environmental exploration, industrial production and other fields has been continuously upgraded, promoting robot research to show a trend of accelerating breakthrough in macro expansion, micro deepening and extreme environment fields. Especially under the background of China's implementation of major scientific and technological strategies such as deep space, deep sea and deep earth exploration, extreme environment operations face many scientific and technological challenges, and extreme environment robots become the core means to break through the bottleneck of traditional operations by virtue of environmental adaptability design and autonomous decision-making ability.

Extreme environment refers to areas where physical, chemical and biological conditions seriously deviate from the normal survival range of Earth species, such as extremely high and low temperature polar regions, volcanic craters, high pressure deep

sea and vacuum space, etc. These areas are of great significance to human scientific research and development, and special robots are needed to replace human beings to carry out work.

Current research focuses on technological breakthroughs in single extreme scenarios, lacking systematic integration of common technology requirements and differentiated scenarios. Based on the three-dimensional framework of "demand-technology-case", this paper systematically analyzes the key technology system of extreme environment robots, reveals the common challenges and differentiated requirements in technology landing, and proposes a full-chain development path covering basic research, application development and standard formulation, providing theoretical and practical support for intelligent transformation of extreme environment operation.

Human exploration of extreme environments began in the 20th century, from 1949 when the American M1 robotic arm handled nuclear materials to 2020 when the Striver reached ten thousand meters deep, and related robotic technology has evolved from remote control to multi-machine collaborative and bionic structure operations. This paper further explores the fusion of large model artificial intelligence, intelligent perception technology and robots, aiming at building a new extreme robot with autonomous decision-making ability and providing a theoretical optimization path for its underlying logic design.

2 Critical Technologies for Extreme Environments

2.1 Mechanical Structure and Materials

Seal Structure Design. In extreme environments, in order to prevent the internal precision equipment of the robot from being negatively affected by the external environment, it is necessary to seal several key components of the robot to ensure its normal operation, extend its service life and adapt to different working environments. For example, in the reducer, most of the input and output ends use oil seals to prevent gear wear powder from invading the seal interior and ensure stable operation of the reducer; combined seals can also be used, such as oil seals with three-lip design, which can effectively prevent foreign matter from invading and adapt to frequent alternating conditions of positive and negative rotation. In the joint part, generally use O-ring to seal the connection between parts, at the same time can also use a radial oil seal, to ensure the joint part the sealed, prevent oil leakage. In robots that require pneumatic or hydraulic drive, sealing rings are generally used to seal against gas or liquid leakage [1].

Motion Mechanism Design. Motion ability is the basis of ensuring the normal work of robots. Extreme environment robots need to adapt to various complex geographical environments to complete operations, such as small spaces, many obstacles, and strong pressure environments. Therefore, it can adopt different motion mechanism designs

according to different environments and different needs. For example, leg-type walking mechanism has the advantages of terrain adaptability and strong stability, but its control system is complex and the control method needs to be improved; wheeled walking mechanism has simple structure, fast movement speed, high energy utilization rate, good maneuverability on flat roads, but poor terrain adaptability, and it is difficult to maintain the original high maneuverability in rugged mountains; Crawler-type traveling mechanism has strong terrain adaptability, good mobility, strong off-road ability, strong passability in complex road conditions such as mountains and mines, but its structure is complex, its weight is large, its shock absorption function is poor, and its parts are easy to damage [2].

Temperature Control. Through proper thermal management techniques such as thermal insulation, robots can survive extreme temperatures and temperatures, such as Mars, polar regions, craters, etc., while protecting the delicate experimental materials inside the machine. The nano aerogel thermal insulation device of Zhurong Mars rover [3] ensures the normal operation of the Mars rover with very little weight and shows extremely high stability through thermal insulation performance design, mechanical performance design, excess control, exhaust design and special materials.

3 Intelligent Control

Facing the extreme working environment with harsh and complex conditions, the robot needs to collect environmental variables such as temperature and humidity through sensors and use artificial intelligence algorithms to summarize the data and extract useful numerical information from them. The large model framework is used to analyze them. After the results are obtained, the next instructions are issued to the robot's working behavior to ensure the safety of the robot's work and the integrity and accuracy of the collected data.

3.1 Intelligent Perception

The core function of intelligent perception is to enable robots to understand their operating environment. Firstly, it is necessary to construct a multivariate neural network to collect environmental physical and chemical signals comprehensively and dynamically in real time. After preprocessing, the collected raw data are transmitted to artificial intelligence modules that have been calibrated by large model training. These modules perform key multimodal data fusion processing, and perform pattern recognition and state inference on the current environment according to the learned underlying logic form. Through this process, the robot realizes synchronization, multi-dimensional analysis and understanding of the surrounding environment.

Cross-domain technology fusion has become a key path to break through the bottleneck of robot intelligent perception performance in extreme environments. Through complementary method integration, multi-modal data collaborative perception and intelligent decision-making are systematically realized. The spatial feature extraction ability of the convolutional neural network (CNN) and the modeling

advantage of the Transformer are fused to construct a framework that can simultaneously perform multi-target real-time detection and hybrid calculation, significantly improving the cognitive effect of complex dynamic scenes [4]. Further, high-precision GPS positioning technology and risk-aware path planning algorithm form a closed-loop optimization mechanism to enable robots to achieve high positioning accuracy and adaptive obstacle avoidance capability in abnormal environments such as polar glaciers and deep-sea hydrothermal zones, and establish a reliable navigation guarantee for scientific investigation and resource exploration missions [5]. At the same time, map construction technology combines real-time sharing data of group state to construct a collaborative perception network of a multi-robot system, effectively avoiding workspace conflict through real-time sharing of environmental information and task state data, and forms a swarm intelligence effect with spatial collision avoidance and task synergy [6].

3.2 Intelligent Decision-making

Intelligent decision-making refers to focusing on normative analysis and executive analysis, using visual tools and computational models to model, and achieving the purpose of visually displaying the decision-making process. Robot intelligent decision-making can deal with a complex environment, evaluate risk coefficients, and finally reduce work risk and realize real-time judgment on environmental conditions and issue accurate operation instructions.

The traditional decision mode of a robot is a manual preset rule set. The robot matches the collected data. Although it has the simplicity of operation and can make real-time decisions, this method has a limited ability to deal with a complex environment, and the number of rules tends to increase exponentially after later optimization. Moreover, robots with poor generalization ability are doomed to work only in specific scenarios and have poor learning ability. After fusion training, the large model can store a large number of related rules, and then reasoning through feature matching can significantly reduce decision bias. Simultaneous processing of multi-source heterogeneous data and dynamic optimization can not only process dynamic environmental data, but also achieve self-adaptation of decision model parameters and improve adaptability to unknown environments [6]. Through graph theory to characterize the dependency relationship between units, a logic network of "robot-task-environment" can be constructed, and the task assignment scheme can be optimized by cross-mutation operation for the multi-robot task overlap phenomenon [7]. Based on deep reinforcement learning, the robot can make real-time decisions on the optimal solution during the movement process. At the same time, the introduction of an attention mechanism can strengthen the robot's attention to specific areas, rank the importance of behaviors and work in real time, and prioritize the options with the highest urgency [8]. In complex environments, adaptive sliding trajectory tracking control and disturbance compensation are used to force the error to converge quickly to zero and suppress external disturbances [9].

3.3 Intelligent Execution

Intelligent execution refers to the ability system to transform high-order decisions into safe, accurate and adaptive action outputs in dynamic physical environments. The

essence is to make the robot complete autonomous and accurate work behavior through perception-decision-execution closed-loop optimization. Executive intelligence can realize the interaction between decision-making and executive behavior, and can suppress dynamic disturbance and ensure the accuracy of work.

Force-based feedback interaction and visual-sensing interaction can provide visual and force signals for decision making. Based on physical attribute modeling, a mapping model is constructed for the orientation and grasping point of force, and a corresponding working scheme is adopted for different materials. The flexible grasp control technology adopted can adjust the actuator strength algorithm to achieve fine control of grasping strength [10]. A gait generation method based on a deep reinforcement learning framework trains agents to generate corresponding gait execution schemes for different terrains. By monitoring the robot center, centroid and other parameters in real time and using them as feedback control data, the gait stability adaptive optimization mode can be achieved [11].

4 Application Field

4.1 Deep Sea

Such as unmanned submersibles, and seabed resource exploitation. Water pressure rise is a major problem. The enormous water pressure at sea depths poses a safety threat to the structural integrity and materials of robots, and in order to ensure proper operation and safety of robots, robot materials and designs must withstand these extreme conditions. Structural design plays a key role in sealing deep-sea robots at high water pressures, enabling them to complete underwater missions. Deep-sea robots also face difficulties such as poor lighting conditions and image recognition, which seriously affect perception sensors. The high absorption of light in the deep-sea environment limits lighting conditions. Therefore, professional technologies such as ultra-, infrasound and infrared sensors need to be used to support the completion of the job. For example, the acoustic and control systems of Jiaolong are key technical modules of manned submersibles, which are applied to deep-sea exploration operations; Seagod adopts a hybrid design, and its biggest technical breakthrough is to use special ceramic materials to manufacture pressure tanks, which have both high strength and lightweight characteristics.

4.2 Underground

The underground environment is complex and changeable, including earth pressure and crustal movement, which brings difficulties to the operation of underground robots. In order to ensure the safety and efficiency of robot operation in this environment, tactile sensors can be used to sense the surrounding soil conditions and crustal movements before carrying out operations. Underground robot needs to analyze geological information, robot arm position, force point, etc., to formulate a motion plan. Traditional underground excavation operations typically rely on large machines with rigid and oversized components to overcome soil particle resistance. However, Naclerio et al. [12] have successfully used a soft robot that can achieve high speed penetration

of the ground and underground excavation by controlling underground interaction forces [13].

4.3 Rescue and Rescue

Robots can also play a huge role in disasters such as fires and earthquakes. Firefighting robots can greatly improve the safety of human rescue, instead of entering high-risk environments such as high temperatures, toxic chemicals, radioactive sites and other extreme environments where humans cannot survive. Minimize and avoid firefighter casualties. Special fire-fighting robots have ultra-high temperature resistance and can work in the core area of the fire, performing tasks such as searching for survivors and detecting explosives [14]. At the same time, the robot can also carry more equipment through its load capacity beyond the human body. For example, the UAV can quickly send a large number of robots equipped with life detectors to the earthquake center by airdrop, collect on-site information 24 hours a day and transmit it to the headquarters, so as to help rescue commanders make scientific judgments and plan for the disaster situation in time.

5 Technological Challenges and Future Developments

5.1 Lunar Robot Cluster

Space has inexhaustible energy, the future of mankind will certainly exploit space energy, and the moon is the closest satellite to mankind. Considering that human survival in space requires a lot of resources and money, and requires life support equipment and life cycle equipment, robots will be the "pioneers" to replace humans in space exploration. Construction from a large number of deep-learning space robots using local materials is an excellent option for lunar base construction.[15] There are still some problems with current technology, such as the lack of GPS positioning on the moon, which makes it impossible for machine clusters to coordinate accurately, the limited communication between the Earth and the moon, and energy problems.

5.2 Nuclear Accident Rescue

With the pursuit of clean energy, nuclear energy has become a popular way to generate electricity for reasons such as environmental protection and large power generation. But mankind can never guarantee that there will be no nuclear leakage incident. Nuclear power plants need robots [16] to help human rescuers quickly discover the source of the leak at critical times, and to perform a no-return mission when necessary to ensure the safety of rescuers. But there are still a lot of problems, such as mechanical anti-radiation problem, communication problem in a strong electromagnetic interference environment, map real-time update problems after an accident, etc.

6 Conclusions

This paper provides an overview of the development of extreme environment robots from the perspectives of mechanical materials and intelligent control, while also

highlighting current and future technological advancements and their applications in various fields. In the field of extreme robots, significant breakthroughs have been achieved in exploration directions such as deep underground and deep-sea environments. For example, the small deep-sea robot developed by Professor Wen Li's team can already operate at depths of 10,000 meters, but it still cannot achieve swarm collaboration or perform large-scale tasks. This is fundamentally constrained by insufficient edge computing power, energy shortages, and inadequate material strength. In the future, breakthroughs in quantum positioning systems, the integration of small-scale ultra-high-performance intelligent systems, and the development of materials adapted to specific environments will be necessary to achieve the intelligentization and unmanned operation of robots in extreme environments.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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