The evolution of robot-driven system from traditional driven system to intelligent flexible system

Zimo He[1*]

[1]Guangzhou Foreign Language School, Guangzhou, 510000, China

Abstract. As the core of robots, the drive system's performance dictates robots' mobility, adaptability and task efficiency. This article reviews the evolution of robot drive tech, from traditional motor drive to flexible drive based on smart materials and bionics, analyzing advantages, limitations and principles of various drive technologies. It summarizes operation modes of traditional motor, pneumatic and hydraulic drives, and principles of new drives like shape memory alloy, bionic drive, dielectric elastomer and pneumatic artificial muscle. Moreover, it introduces progress in cutting-edge areas: multimodal drive cooperative control optimizing motion synergy, human-machine interaction force perception enhancing operational safety, and extreme environment adaptability designs boosting durability. It also discusses technical bottlenecks such as material fatigue and energy loss, along with future trends like intelligent adaptive control. Currently, key research focuses on robots' autonomous operation in extreme environments for high-precision tasks. The article offers theoretical references for interdisciplinary innovation, integrating biology and bionics to enhance robots' movement and efficiency in specific environments.

1 Introduction

Under the global wave of industrial intelligence transformation and the upgrading of high-end equipment demand, robots have rapidly permeated from traditional industrial scenarios into complex fields such as medical rehabilitation, deep-sea exploration, polar scientific research, and humanoid services. As the core of robots, the performance of the drive system directly determines the robot's motion accuracy, load capacity, and environmental adaptability. The background of the research question thus becomes prominent. At present, the diversification of robot application scenarios poses more stringent requirements for drive technology: industrial robots need to maintain millimeter-level positioning accuracy during high-speed operation to adapt to precision manufacturing; Bionic robots need to simulate the flexible drive of biological muscles to achieve flexible movement in complex terrains. Deep-sea exploration robots need to withstand a high pressure of 10,000 meters without reducing their driving efficiency. However, the existing drive technologies still face multiple bottlenecks. For instance, the

* Corresponding author: sky67380008@outlook.com

power density of servo motors is limited by the magnetic properties of silicon steel sheets and the Curie temperature of permanent magnets. Flexible drives are prone to sudden changes in material modulus and attenuation of drive amplitude in extreme environments. These contradictions have become the core obstacles restricting the expansion of the application boundaries of robots.

The significance of researching robot drive technology is reflected in two dimensions: From an industrial perspective, the autonomy of high-end drive components is the key to breaking through the bottleneck of the robot industry; From a technical perspective, the innovation of driving technology can in reverse drive the integration and breakthroughs of multiple disciplines such as materials science, control algorithms, and energy management. For instance, the research and development of bionic flexible drives need to combine electroactive polymer materials with biomechanical analysis, and multi-modal collaborative control needs to overcome the challenges of sensor data synchronization and real-time decision-making. The research results can be extended to fields such as aerospace and medical equipment.

In terms of the current research status, the semi-direct drive technology (QDD) proposed by MIT has been applied to the quadruped robot Cheetah. By combining high-torque motors with low transmission ratio reducers, it achieves high dynamic response and torque control. The power density of the joint motor of Tesla's Optimus humanoid robot reaches 8kW/kg, achieving miniaturization and high efficiency through precise manufacturing processes.

2 Traditional drive technologies

2.1 Motor drive system

The core principle of the motor drive system is based on Faraday's law of electromagnetic induction. It achieves precise position control through servo motors, stepper motors, etc., and outputs power in conjunction with transmission mechanisms such as reducers and couplings. Some typical applications include industrial robotic arms and mobile robots. Its technical advantages lie in high precision, often being able to control errors to the millimeter level. At the same time, it has relatively high energy conversion efficiency and mechanical efficiency, and is standardized and mature. Its limitation lies in its inability to adapt to complex environments, and at the same time, it has significant bottlenecks in the changes towards light-weighting and miniaturization.

2.2 Hydraulic and pneumatic drive

Both hydraulic and pneumatic drives are based on Pascal's law and the fluid momentum theorem, using the pressure of fluids to achieve energy transmission, motion control, and power output. Hydraulic drive uses hydraulic oil as the working medium. Relying on the incompressibility and high energy density of liquids, it is often used in heavy-load scenarios. Its advantages lie in the ability to output a huge thrust with a relatively small volume. Through valve control, precise control of position and speed can be achieved. At the same time, it can maintain stable operation in harsh working environments. Application cases include shield machines and excavators. Cranes, etc. The shortcomings of hydraulic drive lie in its low system working efficiency, high maintenance costs, restricted application environment, and the leakage of liquids such as hydraulic oil, which can cause environmental pollution and pose a threat to human health. Pneumatic drive uses compressed air as the working medium. By taking advantage of the compressibility of gas and low-cost consumption, it is suitable for high-frequency, high-speed, and light-load operations. Its advantages lie in low cost, fast response speed, strong environmental adaptability, and high safety. Application cases include printers, elevator doors, food packaging, etc. Its shortcomings lie in the low torque density. The force generated under the same volume is much less than that of hydraulic drive, the control accuracy is low, the stability is poor, and noise will be produced due to the fast gas flow rate.

3 New drive technologies

3.1 Flexible drive technologies

3.1.1 Shape memory alloy drive

SMA is a commonly used driving material for soft robots. It can eliminate the deformation that occurs at low temperatures after being heated and return to its original shape. It features good biocompatibility, simple manufacturing, low cost, light weight, high power density, strong driving force and large driving displacement. Soft robots made of SMA material can not only crawl, twist and grasp, but also perform jumping movements. At present, the disadvantages of SMA are that the material is prone to aging, the output force is relatively small, the driving temperature is difficult to accurately control, and the driving frequency is low.

For example, in 2011, the GoQBot robot developed by B.A.Trimmer's research group at Tufts University was based on curved reptile and driven by SMA [1]. It can simulate the movement of caterpillars and complete actions such as crawling and curling. In 2013, H.J.Kim and others from Seoul National University] developed a turtle-like swimming robot that can perform swimming movements by controlling the Angle between SMA filaments [2]. This turtle-like robot can bend 55mm and twist 24°. In 2017, W.Wang and others developed a flexible gripper driven by SMA [3]. This gripper can perform adaptive grasping in a low-stiffness state and effective grasping in a high-stiffness state.

3.1.2 Dielectric elastomers (DE) and pneumatic artificial muscles (PAM)

DE drive is that under the action of an electric field, the elastomer film deforms, with a power density as high as 1000W/kg, approaching the level of biological muscle, but it requires high-voltage drive at the kilovolt level.

PAM drive, for instance, the McKibben muscle can achieve an axial contraction rate of up to 40% under pneumatic drive and has been applied to the finger joints of rehabilitation robots (with a bending Angle of up to 120°). Moreover, their bottlenecks are long-term stability of DE and nonlinear hysteresis compensation algorithm of PAM [5].

2.3 Bionic drive technology

The core of bionic drive technology is to design and develop artificial drive systems with similar biological movement characteristics, such as flexibility, efficiency and adaptability, by imitating the movement mechanisms, drive structures or energy conversion methods of organisms in nature, such as animals, plants and microorganisms, in order to simulate, optimize or expand the movement functions of organisms. Meet the motion control requirements in specific scenarios.

For instance, bionic fish that imitate the swimming of fish achieve efficient movement based on the wave drive of the body-tail fin pattern, such as the MIT bionic fish Robotuna, whose propulsion efficiency is 25% higher than that of traditional propellers. In addition, bionic robots that imitate insect jumps to achieve movement have increased the energy density of their drive units to five times that of traditional motors by imitating the elastic energy storage structure of flea legs [6].

4 Research Progress on Core Technologies of Drive Systems

4.1 Multimodal driven cooperative control

Multimodal drive cooperative control is a technology that organically integrates various different types of drive methods (such as motor drive, hydraulic drive, pneumatic drive, bionic drive, etc.) and makes them work in coordination through corresponding strategies, thereby achieving more efficient, flexible and precise control and task execution capabilities.

The key components of a multimodal drive system include the sensor system and the control algorithm system. The sensor system is used to obtain real-time status information of the system and information about the external environment it is in, so as to make the most reasonable actions and provide data support for the calculation of core algorithms. Common sensors include position sensors, force sensors, speed sensors, tactile sensors, etc. The control algorithm system is the core for achieving multimodal collaborative drive. It coordinates and controls each module based on the information provided by sensors to achieve the optimal collaborative effect. During this process, it needs to consider the characteristic differences among different drive modules, such as speed and response time [7].

4.2 Extreme environmental adaptability design

Adaptive design for extreme environments requires the collaborative completion of multiple aspects such as materials, structures, and energy. For instance, in high-temperature environments, by using a graphene-fish-carbon nanotube composite heat dissipation layer in combination with micro-channel liquid cooling technology, the temperature of the chip can be significantly reduced. In low-temperature environments, the use of electroactive polymers can maintain driving performance through self-heating at minus 50 degrees. In highly corrosive and radiative environments, the use of polyurea protective layers and epoxy mica intermediate paint can withstand the erosion of strong alkali and strong acid.

The structural design for extreme environments aims to transform environmental challenges into driving advantages. In the high-pressure environment of the deep sea, the bistable chiral metamaterial structure developed and researched by the Beihang University team increases the material modulus by taking advantage of the high pressure in the deep sea, and the driving amplitude and speed increase in the opposite direction, achieving efficient movement. This pressure-boosting design breaks through the performance degradation bottleneck of traditional flexible drivers under high pressure. In the polar low-temperature environment, a three-stage nested insulation structure can be adopted, namely the inner layer of graphene aerogel, vacuum aluminum foil reflective layer, and boron nitride nanotube matrix, which can achieve extremely high insulation efficiency even in extremely low-temperature conditions.

In extreme environments, robots often adopt hybrid energy systems. For instance, polar research robots use wind power generation and lithium-ion batteries, and achieve dynamic energy distribution through algorithms. They can operate for up to 72 hours in low-temperature conditions [8].

5 Challenges and Future Trends

5.1 Current technical bottleneck

The current technological shortcomings include the limitations of core component materials. Constrained by physical bottlenecks and purity issues of the materials, how to achieve continuous operation, low energy consumption and high extraction efficiency remains a problem that needs to be solved. The mismatch between control algorithms and hardware, multimodal collaboration and intelligent algorithms all exhibit real-time system delays, leading to the occurrence of errors. Performance degradation under extreme conditions: In extreme environments, the aging and wear of materials can lead to short circuits in circuits, prolonged response times, and other issues.

5.2 Frontier development directions

Robot drive can be studied in the direction of biological hybrid drive. Through the interface technology between skeletal muscle cells and electrodes, biological energy can be directly converted into mechanical energy. Quantum drive, a nanoscale drive unit based on the quantum tunneling effect, has a theoretical positioning accuracy that can reach the atomic level. The self-healing drive system utilizes shape memory polymers and microcapsule self-healing materials to achieve autonomous repair of damage to the drive structure

6 Conclusion

Robot drive technology is evolving from "single rigid drive" to "intelligent flexible collaboration". In the future, breakthroughs need to be made in areas such as multi-physics coupling modeling, cross-scale drive design, and energy sustainability. With the deep integration of smart materials, bionics and artificial intelligence, drive systems will be more environmentally sensitive, human-machine collaborative and autonomous adaptive, promoting the large-scale application of robots in scenarios such as medical care, deep space exploration and emergency rescue.

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