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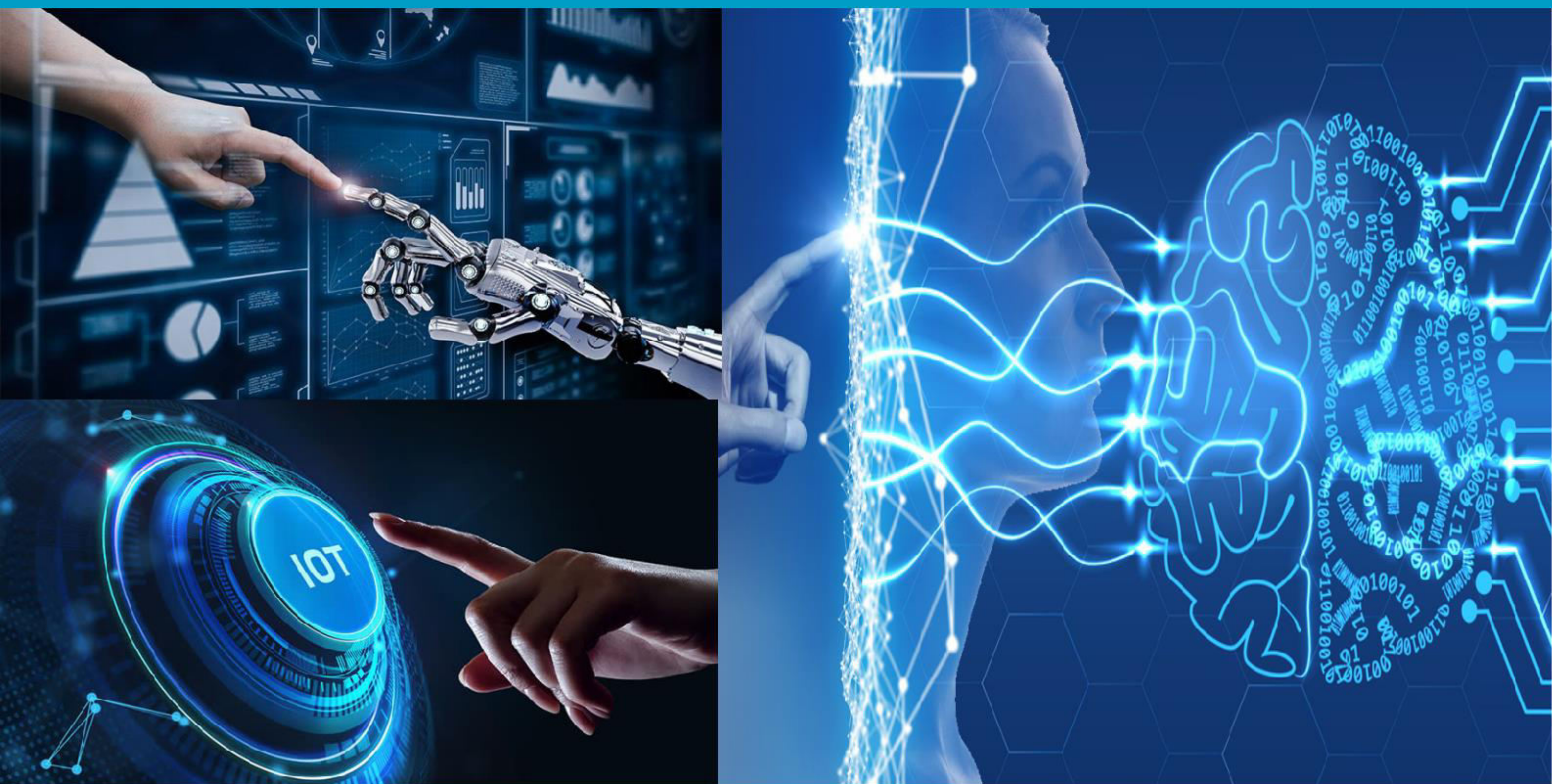

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Palletizing Robots: Technology Evolution, Application Expansion and Future Prospects

Jing Lei [1*], Jia-Qing Song [2], Hui Zhang [1], Yan Chen [1], Ji-Yan Wang [1]

School of Mathematics and Statistics, Taishan University, Tai'an, China[1]

Experimental Teaching Management Center, Taishan University, Tai'an, China[2]

ABSTRACT: This paper focuses on palletizing robots and systematically expounds their key role in the process of industrial automation. The working principle of palletizing robot based on "perception-decision-execution" and the core technologies such as mechanical structure design, control system, sensor technology, and artificial intelligence technology were introduced. The characteristics of different types of palletizing robots such as Cartesian coordinates, joint type, and parallel connection are discussed, and their application scenarios and effects are analyzed through actual cases in food, chemical, logistics and warehousing industries. Studies show that palletizing robots are developing in the direction of intelligent upgrading, modular design, human-machine collaboration, greening and energy saving, but they are also facing challenges such as technical bottlenecks, costs, talent shortages and market competition. This study provides a comprehensive and in-depth reference for the further development of palletizing robots.

KEYWORDS: Palletizing robot; Core technology; Fields of application; Development trends; Challenge

I. INTRODUCTION

1.1 Background and significance

In the wave of industrial automation, palletizing is a key link in production and logistics, and the limitations of traditional manual palletizing are becoming more and more prominent. Problems such as high labor intensity, low efficiency, easy to make mistakes and difficult to adapt to harsh environments can no longer meet the needs of modern industrial high-speed, accurate and continuous production. The birth of palletizing robots provides solutions to these problems. It can continue to operate, greatly improve palletizing efficiency, reduce labor costs, and reduce cargo damage and stacking errors with precise control. In harsh environments such as high temperatures, dust, and harmful chemicals, the palletizing robot operates stably to ensure production safety and continuity. According to data from the International Federation of Robotics (IFR), the annual growth rate of the global palletizing robot market has reached 12% in the past five years, highlighting its important position and broad prospects in the industrial field, and is of great significance to promoting industrial intelligence and automation upgrades and enhancing the competitiveness of the national manufacturing industry.

1.2 Research status at home and abroad

Foreign companies in Europe and the United States and Japan such as ABB, KUKA, and Fanuc with deep R&D accumulation and advanced technology have launched high-performance and high-reliability products, which are widely used in many industries. Foreign scholars have conducted in-depth research on cutting-edge technologies such as robot kinematics, dynamic optimization, high-precision control algorithms and multi-sensor fusion, and continue to improve the performance and intelligence level of palletizing robots.

The domestic palletizing robot industry has developed rapidly in recent years, and driven by policy support and market demand, universities, scientific research institutions and enterprises have actively invested. Some domestic enterprises have achieved breakthroughs in key technologies, and their product performance has moved closer to the international advanced level, relying on price advantages and localized services to occupy a certain share in the domestic market. However, compared with developed countries, there is a gap in the manufacturing of core components (such as high-precision reducers, servo motors), high-end technology research and development and product stability, and there is also a lag in the integration and application of cutting-edge technologies such as artificial intelligence and big data and palletizing robots. At present, the adaptability of palletizing robots in complex environments and the safe and efficient collaborative work in human-machine collaboration mode are still the weak links in research.

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II. THE BASIC PRINCIPLE AND CORE TECHNOLOGY OF PALLETIZING ROBOTS

2.1 Rationale

The palletizing robot operates on the closed-loop control principle of "perception-decision-execution". In the perception link, visual, force, proximity and other sensors collect material location, shape, weight and surrounding environment information in real time. The visual sensor recognizes the shape, size and posture of the material through two-dimensional or three-dimensional imaging and image processing algorithms, and provides a position basis for grasping and stacking. The force sensor monitors the gripping force during gripping to prevent material damage or dropping.

In the decision-making process, the control system analyzes the perception information, combines the preset palletizing task requirements (stacking type, stacking sequence, etc.), and uses algorithms to plan the optimal motion path and action sequence, such as using the path planning algorithm to plan a collision-free and efficient trajectory for the robotic arm in a complex space, and adjusting the grasping attitude and strength according to the characteristics of the material with the help of intelligent algorithms.

In the execution link, the mechanical structure accurately executes the grabbing, handling and stacking actions according to the instructions of the control system. The robotic arm is driven by a motor to rotate or move the joint, so that the end effector can accurately reach the target position and operate according to a predetermined attitude. During the whole process, the control system continuously compares the actual movement status of the robotic arm with the planned path to ensure the accuracy and stability of the palletizing operation.

2.2 Core Technology

2.2.1 Mechanical structure design

The common mechanical structures of palletizing robots include Cartesian coordinate type, joint type and parallel type. Cartesian coordinate palletizing robot is composed of X, Y, Z linear motion axis, simple structure, high motion accuracy, horizontal and vertical positioning error can be controlled within ±0.5mm, easy to program and maintain, suitable for electronic components palletizing and space regulation warehouse operations, but the movement speed is slow, the working space is limited and the flexibility is not good.

The articulated palletizing robot simulates the joint movement of the human arm, generally with 4 - 6 degrees of freedom, and the motor drives the joint rotation to realize the multi-directional movement of the robotic arm, with extremely high flexibility, and can complete irregular stacking in complex spaces, with a large working range, fast movement speed, strong load capacity, and can handle dozens of kilograms to several tons of goods. However, its structure is complex, and the establishment of kinematic models and the design of control algorithms are difficult and costly.

The parallel palletizing robot adopts a parallel mechanism, and realizes the movement of the end effector by connecting the moving platform and the fixed platform through multiple branch chains. Compact structure, high rigidity, extremely high movement speed and acceleration, in the high-speed placement production line of the electronics industry, the repeated positioning accuracy can reach within ±0.1mm, the dynamic performance is good, and the impact of vibration and shock on the material during high-speed movement can be reduced. However, its working space is relatively small, and the manufacturing process and assembly accuracy are demanding. In order to meet the diverse needs, new mechanical structures are emerging, such as retractable robotic arms and flexible material robotic arms.

2.2.2 Control system

The palletizing robot control system consists of two parts: hardware and software. In terms of hardware, industrial computers or programmable logic controllers (PLCs) are used as core controllers, with high-performance servo drives, motors, various sensors and communication interfaces. The industrial computer has strong data processing capabilities and is suitable for high-end systems; PLC has high reliability, simple programming, strong anti-interference ability, and is widely used in low-end systems. The servo drive and motor accurately control the movement of the robotic arm, the encoder monitors the rotation angle of the motor and feeds back the position of the robotic arm, the gyroscope detects the attitude change, the communication interface realizes information interaction, and the common communication protocols include Ethernet, CAN bus, etc.

In terms of software, the control system software includes motion control algorithms, path planning algorithms, task management systems, and human-computer interaction interfaces. The motion control algorithm is the core, which calculates the motor control instructions according to the target position and attitude information, and the common algorithms include PID control, adaptive control, sliding mode control, etc. Path planning algorithms plan collision-free optimal paths in the workspace, and commonly used algorithms include A* algorithm, Dijkstra algorithm, and Fast Exploration Random Tree (RRT) algorithm. The task management system schedules and manages palletizing tasks, the human-computer interaction interface provides a convenient operation platform for operators, and some advanced interfaces support gesture recognition, voice control and other functions.

2.2.3 Sensor technology

Sensors are the basis for the intelligent and precise operation of palletizing robots. Vision sensors are used in a wide range of applications, including two-dimensional vision and three-dimensional vision. The 2D vision system acquires a 2D image of the material via an industrial camera, which is identified, located and measured by an image processing algorithm, e.g. to inspect package integrity and label position in the food packaging industry. The 3D vision system obtains the 3D spatial information of materials, and the common technologies include structured light 3D imaging and laser scanning 3D imaging, which have obvious advantages in the identification and positioning of materials with irregular shapes and complex environments.

Force transducers measure the forces and moments when robots grip and handle materials, and the common ones are strain gauge, piezoelectric and six-dimensional force transducers. The strain gauge type has a simple structure and low cost; Piezoelectric response speed and high precision; Six-dimensional force sensors can measure forces and moments in three directions at the same time, which is important for palletizing tasks that require high force control, such as precision assembly. In addition, the palletizing robot may also be equipped with proximity, temperature, pressure and other sensors, and the fusion of multiple sensors provides the robot with richer and more accurate environmental information, improving its adaptability to complex working conditions and operation accuracy.

2.2.4 Artificial intelligence technology

Artificial intelligence technology promotes the intelligent development of palletizing robots. Machine learning algorithms collect and collate historical palletizing task data, and train robot models using supervised learning, unsupervised learning, or reinforcement learning algorithms. Supervised learning learns the mapping relationship between input and output according to labeled sample data, unsupervised learning discovers potential patterns and rules of data, and reinforcement learning allows robots to learn optimal behavior strategies in interaction with the environment. Deep learning has achieved remarkable results in visual recognition and intelligent decision-making of palletizing robots. The convolutional neural network (CNN) based on deep learning performs well in the visual recognition of materials, and the training model by constructing image datasets can achieve fast and accurate classification and positioning of materials, which has higher accuracy and stronger generalization ability than traditional visual recognition methods. In terms of intelligent decision-making, deep learning and reinforcement learning are combined, robots use deep learning models to perceive and understand the operation scene, and then make optimal decisions through reinforcement learning algorithms, and can also use technologies such as generative adversarial networks (GANs) for virtual simulation and optimization.

III. TYPES AND CHARACTERISTICS OF PALLETIZING ROBOTS

3.1 Cartesian coordinate palletizing robot

The main body of the Cartesian coordinate palletizing robot is composed of three linear motion axes perpendicular to each other X, Y, and Z, and the linear motion is realized by the motor driving the lead screw nut pair or rack and pinion pair. Under ideal working conditions, its positioning accuracy can reach ±0.2mm in the horizontal direction (X, Y axis) and ±0.3mm in the vertical direction (Z axis), which is suitable for industries with extremely high precision requirements such as electronic component manufacturing. Its load capacity can be customized, the small one is generally 1 - 10kg, which is used for lightweight material palletizing; The medium-sized ones are 10 - 50kg, which are suitable for palletizing small and medium-sized packaged products in food and medicine; Large ones can reach 50 - 500kg, which can cope with heavy materials in the building materials and metal processing industries. The workspace is rectangular in shape, and the axis travel can be designed according to the site and job needs. Its structure is simple, high reliability, easy maintenance, simple motion control algorithm, low difficulty in programming and debugging, and the horizontal and vertical movement speed can be adjusted independently. However, the flexibility of movement is poor, and the handling of irregular shapes and messy layout materials requires complex teaching programming or high-precision visual positioning assistance, and the working space is limited by a rectangular area.

3.2 Articulated palletizing robots

Articulated palletizing robots typically have 4 to 6 degrees of freedom of rotation joints, driven by high-performance servo motors, with torque amplification and precise angle control through reducers. It can realize complex movement trajectories, and can easily cope with the stacking of packaging containers of different shapes and sizes in the food and beverage industry. Large load capacity span, small handling of 5 - 20kg load, for 3C product manufacturing; Medium-sized load range of 20 - 100kg, widely used in food, daily chemical industry; the large ones can carry heavy loads from 100 to 2000kg, and are used in automobile manufacturing, building materials and other industries. The workspace is centered on the base of the robot, which is approximately spherical or hemispherical in shape, covering a wide area. It has high flexibility, can quickly adapt to changes in material and palletizing requirements, and has fast movement speed, which has obvious advantages in scenarios with high efficiency requirements such as e-commerce logistics warehouses. However, the mechanical structure is complex, the kinematic and dynamic analysis is difficult, the control system algorithm design and computing power are required, and the maintenance difficulty and cost are relatively high.

3.3 Parallel palletizing robots

The parallel palletizing robot is based on the parallel mechanism, which connects the moving platform and the fixed base through multiple branch chains, and the end effector is installed on the moving platform. The movement speed and acceleration are extremely high, and in the high-speed placement production line of the electronics industry, the frequency of action can reach dozens of times per second, and the repeatability of positioning can reach within ±0.1mm or even higher. Load capacity varies depending on model and design, the small one is used for light-load, high-speed, high-precision scenarios, with a load of 1 - 5kg; The medium-sized one is suitable for palletizing small and medium-sized packaged products in food and medicine, with a load of 5 - 20kg; The large ones are specially designed to handle 20 - 100kg of material. The workspace is relatively limited and takes on a conical or hemispherical shape. In electronic manufacturing, precision instrument assembly and other industries with high requirements for speed and precision, and low requirements for working space, the advantages are prominent, and the structure is simple, easy to clean, and can avoid material pollution in the food and pharmaceutical industries. However, its mechanical structure requires demanding manufacturing processes and assembly precision, and the limited workspace makes it necessary to work in conjunction with other equipment when handling large materials or covering a wide range of work areas.

IV. THE APPLICATION FIELD AND CASE ANALYSIS OF PALLETIZING ROBOTS

4.1 Food industry

4.1.1 Application Scenarios and Requirements

The food industry has a fast pace of production, high hygiene requirements and a wide variety of products. In the packaging process, products with different packaging forms and specifications require robots to quickly and accurately grasp and place according to specific stacking types, such as bottled beverage production lines require high-speed and stable grasping, and bagged foods require precise control of grasping strength. In terms of warehousing and logistics, it is necessary to improve the utilization rate of space and the efficiency of warehousing, adapt to the characteristics of multiple varieties and small batches of e-commerce orders, and the robot material should be corrosion-resistant, easy to clean, and prevent food contamination.

4.1.2 Case Study

A large beverage manufacturer introduced a jointed palletizing robot, which previously palletized about 500-600 cases per hour, which was inefficient and unstable, and the goods collapsed frequently. After the introduction of the robot, the stacking speed per hour has been increased to 1200-1500 cases, the stacking accuracy is high, the stacking pattern is stable, the product loss rate is reduced by about 80%, the labor cost is reduced by about 80%, the operation interface is simple, and the new employees are easy to use.

A bakery company uses Cartesian palletizing robots with a visual recognition system to inspect the quality of its products in a variety of packaging formats. The robot high-precision positioning and grasping, the vision system detects defective products, the production efficiency is increased by about 60%, the defective product rate is reduced by about 50%, and a lot of labor costs are saved.

4.2 Chemical industry

4.2.1 Application Scenarios and Requirements

The production environment of the chemical industry is complex, and there are risk factors such as high temperature, high pressure, strong corrosion, flammable and explosive and a large amount of dust, which has extremely high requirements for the safety, stability and environmental resistance of palletizing equipment. In terms of raw material handling, it is necessary to carry bagged fertilizers, cement, barreled acid and alkali solutions, etc., and to prevent dust. In the process of palletizing finished products, due to the variety of products and different packaging forms, the robot needs to be highly flexible and adaptable, and it must cooperate with other equipment on the production line to achieve an efficient production process.

4.2.2 Case Studies

A large chemical company deployed a heavy-duty joint palletizing robot in a fertilizer production workshop, which was previously labor-intensive, inefficient and harmful to workers' health. After the introduction of the robot, the stacking speed per hour is increased to 800-1000 bags, the efficiency is increased by about 200%, and the protection level

reaches IP65, which can operate stably in harsh dust environments, realize seamless connection with upstream and downstream equipment, and greatly improve the degree of production automation and product quality stability.
A chemical reagent manufacturer uses a customized Cartesian coordinate palletizing robot, which has a variety of product packaging specifications, the robot is equipped with a variety of grabbing tools and an explosion-proof device to achieve high-efficiency palletizing of small batches and multiple varieties of chemical reagents, increasing production efficiency by about 50%, reducing labor costs by about 60%, and avoiding safety accidents.

4.3 Logistics and warehousing industry
4.3.1 Application Scenarios and Requirements
The logistics and warehousing industry has a large flow of goods, a wide variety of goods, and frequent warehousing and warehousing. In e-commerce logistics warehouses, it is necessary to quickly identify, efficiently grasp and flexibly stack a large number of commodity packages of different specifications, and use visual recognition technology and flexible grasping tools to improve space utilization. In the automated three-dimensional warehouse, the palletizing robot should work together with the stacker crane and conveyor, quickly move the goods to the designated location according to the warehouse management system (WMS) instructions, and have the ability to collect and analyze data to optimize the warehouse layout and storage strategy.

4.3.2 Case Study
A large e-commerce logistics center uses palletizing robots to operate in clusters, and the manual sorting and palletizing has low efficiency and high error rate. After the introduction of the robot cluster, through visual recognition and intelligent scheduling system, it can process more than 100,000 parcels per hour, increasing efficiency by several times, reducing the error rate by about 90%, and increasing the utilization rate of storage space by about 30%.
A traditional manufacturing enterprise introduced an automated three-dimensional warehouse system and Cartesian coordinate palletizing robot into the finished product warehouse, which had chaotic warehouse management and low in-and-out efficiency. After the introduction, intelligent management is realized, the goods are stored in an orderly manner, the efficiency of warehousing and warehousing is increased by about 80%, and the inventory accuracy rate is more than 99%, which improves the supply chain management level and market responsiveness of the enterprise.

V. DEVELOPMENT TRENDS AND CHALLENGES OF PALLETIZING ROBOTS

5.1 Development Trends
5.1.1 Intelligent upgrade
With the development of artificial intelligence, big data, and Internet of Things technology, the intelligence of palletizing robots will continue to improve. In the future, robots will have stronger self-learning capabilities, optimize operation strategies based on operation data, and automatically adjust the grasping posture, motion path and stacking sequence in the face of different materials, stacking types and complex environments. With the help of the Internet of Things, it can interact with other equipment on the production line and the enterprise management system in real time, which can quickly respond to production line changes and order adjustments, and also has the ability to predict and self-heal faults to reduce equipment downtime.

5.1.2 Modular design
Modular design will be an important trend. The mechanical structure, control system, and sensors of the palletizing robot will be designed as standardized modules, and enterprises can flexibly combine them according to their own needs and quickly customize the robot system. For example, different grasping and visual recognition modules can be selected for processing a variety of materials, and high-performance motion control and high-precision sensor modules can be selected for high speed and accuracy. The modular design improves customization, reduces procurement costs, makes maintenance and upgrades easier, and extends the life of the robot.

5.1.3 Human-machine collaboration
In the future of industrial production, human-machine collaboration will become the norm. The new generation of palletizing robots focuses on safe and efficient collaboration with human operators. Equipped with advanced safety sensors and intelligent control systems, it can sense the position and movement of personnel, and automatically adjust the movement status to ensure safety. Through the friendly human-computer interface and collaboration algorithms, operators can easily program and assign tasks, and the robot can understand the intent and cooperate closely, giving full play to the advantages of the robot's efficient accuracy and human flexible judgment, and improving the overall efficiency and adaptability of the production system.

5.1.4 Green and energy saving
The global attention to environmental protection and sustainable development has increased, and the palletizing robot will develop towards green and energy-saving. The design and manufacturing process adopts environmentally friendly materials and energy-saving technologies, such as the use of recyclable metals and environmentally friendly plastics to make shells, the use of high-efficiency and energy-saving motors and transmission devices, the optimization of motion control algorithms to reduce energy consumption, and the automatic entry into energy-saving sleep mode when idle, which meets environmental protection requirements, reduces enterprise operating costs, and enhances corporate image and market competitiveness.

5.2 Challenges
5.2.1 Technical bottlenecks
Palletizing robots have challenges in the adaptability of complex environments, the optimization of artificial intelligence algorithms, and the improvement of sensor accuracy. In complex environments, there are many types of materials, different shapes and interference factors, and the recognition accuracy and speed of existing vision algorithms are difficult to meet the needs of fast and accurate operations when dealing with complex scenes, for example, the recognition accuracy of some algorithms in e-commerce logistics warehouses may be reduced to less than 80%. The training of artificial intelligence algorithms relies on a large amount of annotated data, which is time-consuming and error-prone, and it is difficult for algorithms to adapt to dynamic changes in the environment and tasks in practical applications. The sensor is insufficient in terms of high-precision measurement and stability in complex environments, such as the high accuracy requirements of the force sensor for the palletizing of precision electronic components, and some sensors cannot meet the requirements.

5.2.2 Cost issues
The high cost of palletizing robots restricts their popularity. In terms of hardware, the core components (high-precision reducers, servo motors, sensors, etc.) are highly technical, difficult to manufacture and rely on imports, and the cost is expensive, such as high-performance six-axis palletizing robots, and the cost of reducers and servo motors accounts for 40%-50%. The cost of software development and system integration cannot be ignored, and the maintenance cost is high, requiring professionals and equipment, and the annual maintenance cost can reach 10% - 15% of the procurement cost, which is difficult for small and medium-sized enterprises to bear.

5.2.3 Talent shortage
The shortage of professionals in the field of palletizing robots affects the development of the industry. It involves multidisciplinary fields and has high requirements for the comprehensive quality of talents. There is a disconnect between the talent training of colleges and universities and the needs of the industry, the lack of students' practical and interdisciplinary knowledge application ability, the imperfect internal training system of enterprises, and the long talent training cycle. For example, the lack of system integration projects may extend the implementation cycle by 20% - 30% due to the lack of talents, which increases the project cost and operational risk of the enterprise.

5.2.4 Market Competition
With the rapid development of the palletizing robot market, the market competition is becoming increasingly fierce. Many domestic and foreign enterprises have set foot in this field, and the products on the market have a wide variety of products and uneven quality. On the one hand, internationally renowned enterprises occupy a dominant position in the high-end market by virtue of advanced technology, brand influence and perfect service system, which has formed greater competitive pressure on domestic enterprises. For example, the palletizing robot products of ABB, KUKA and other enterprises have obvious advantages in performance, stability and intelligence, attracting many large enterprise customers. On the other hand, there are a large number of domestic enterprises, the phenomenon of product homogenization is serious, and some enterprises adopt low-price competition strategies in order to compete for market share, resulting in chaotic market prices and compressed industry profit margins. This disorderly market competition is not conducive to the healthy development of the industry, but also affects the company's R&D investment and technological innovation capabilities. For example, in order to reduce costs, some small domestic enterprises have not invested enough in product quality and after-sales service, resulting in a decline in customer satisfaction and affecting the reputation of the entire domestic palletizing robot industry.

VI. CONCLUSIONS AND PROSPECTS

6.1 Summary of the study
This study systematically expounds the important position and basic principles of palletizing robots in industrial automation, and deeply analyzes its core technologies such as mechanical structure design, control system, sensor

technology and artificial intelligence technology. Through the analysis of the types and characteristics of Cartesian coordinates, joint and parallel palletizing robots, the differences and applicable scenarios of different types of robots in terms of load capacity, motion accuracy, working space and flexibility are clarified. In terms of application fields, the application scenarios and needs of palletizing robots in food, chemical, logistics and warehousing industries are discussed, and its remarkable results in improving production efficiency, reducing costs, improving product quality and ensuring safe production are demonstrated through actual case analysis. At the same time, the development trend of palletizing robots is prospected, and intelligent upgrading, modular design, human-machine collaboration, and green and energy-saving will become an important direction for future development. However, palletizing robots also face many challenges in the development process, such as technical bottlenecks, cost problems, talent shortages and market competition.

6.2 Future Prospects

Looking forward to the future, there is still huge development potential and research space in the field of palletizing robots. In terms of technological innovation, we should increase investment in complex environment adaptability technology, artificial intelligence algorithm optimization and high-precision sensor research and development, and improve the operation ability and intelligence level of palletizing robots under various complex working conditions. For example, research and development of more advanced visual recognition algorithms, combined with deep learning, reinforcement learning and other technologies, enable robots to quickly and accurately complete palletizing tasks in scenarios with a wide variety of materials and dynamic changes in the environment; We have developed new sensors to improve their accuracy and stability to meet the needs of precision work. In terms of cost control, enterprises should strengthen cooperation with universities and scientific research institutions, increase investment in research and development of core components, improve the localization rate, and reduce hardware costs; At the same time, by optimizing the software algorithm and system integration process, the R&D and maintenance costs are reduced, making the palletizing robot more economical and promoting its wide application in small and medium-sized enterprises. In terms of talent training, colleges and universities should optimize the curriculum of related majors, strengthen practical teaching, and cultivate more professionals with interdisciplinary knowledge and practical ability. Enterprises should establish a sound internal training system, strengthen industry-university-research cooperation with universities, attract and retain outstanding talents, and provide solid talent support for the development of the industry. In terms of market competition, enterprises should pay attention to technological innovation and product quality improvement, strengthen brand building and after-sales service, and improve their market competitiveness through differentiated competition strategies. At the same time, industry associations should play an active role in strengthening the formulation of industry norms and standards, guiding orderly competition in the market, and promoting the healthy and sustainable development of the palletizing robot industry. With the continuous progress of technology and the continuous expansion of applications, palletizing robots will play a more important role in the field of industrial automation and make greater contributions to promoting the transformation and upgrading of the manufacturing industry and economic and social development.

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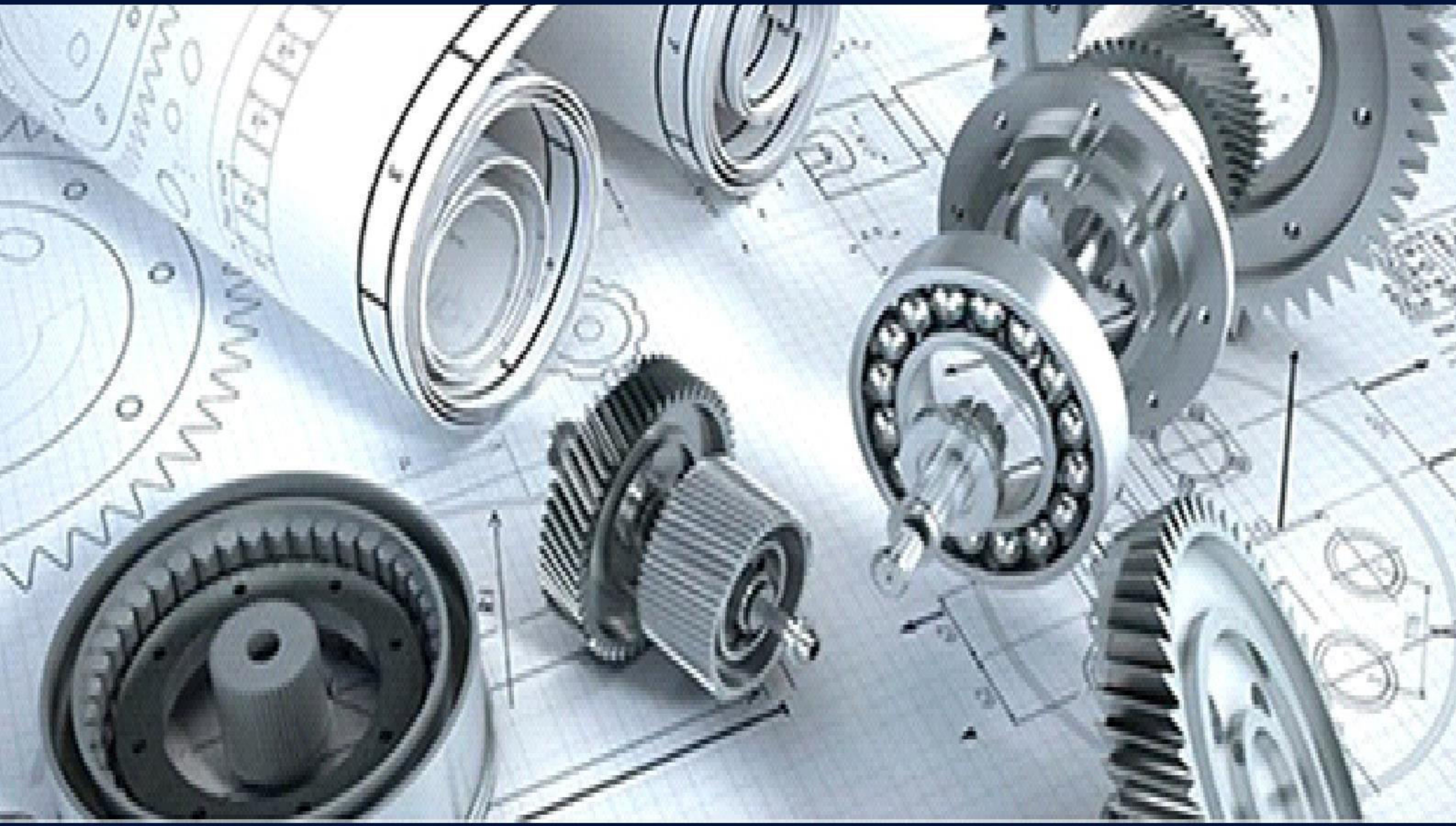

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