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A survey of composite robot for aviation intelligent manufacturing application①

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Abstract

With the rapid development of the aviation industry, the development of intelligent manufacturing equipment represented by composite robots has been paid close attention by the aviation industry. Based on the analysis of the background and main structure function of composite robots, this paper focuses on the analysis of key technologies such as composite robot hardware design, visual sensing and planning system, integrated control of 'hands, feet, and eyes', multi-robot collaborative operation, and safety. The typical applications of composite robots in aviation intelligent manufacturing such as automatic drilling and connection of aircraft, aircraft surface spraying and finishing, parts handling, aircraft measurement, and inspection are presented. The development trends such as standardization of composite robots, integration of '5G + cloud computing + AI', and fusion of intelligent sensors are proposed.

Key words: aviation manufacturing, composite robot, key technology, development trend, safety

0 Introduction

The aviation industry is an important symbol of national technology, economy, and industrialization level. However, facing the challenges of economic globalization, reducing aircraft manufacturing costs, improving performance, and strengthening structural strength have become the common goals of all aircraft manufacturers. The traditional means of development and production mainly rely on the skills of workers, and there are problems such as poor manufacturing consistency, which makes it difficult to meet the needs of modernization and flexibility of the aviation industry. Therefore, composite robots have been widely used in aviation manufacturing factories as a key technology to realize intelligent manufacturing. Due to its repeatability, high rigidity, and high precision, composite robot technology not only improves the quality of aviation equipment, guarantees personal safety, improves the working environment, reduces labor intensity, improves productivity, saves raw materials, reduces production costs and other aspects of remarkable results, but also plays an increasingly important role in the transformation of aviation manufacturing to intelligent manufacturing. It is the inevitable trend of the development of the aviation manufacturing industry in the new era.

1 The connotation and characteristics of the composite robot

1.1 Definition and development of composite robot

The international general definition of composite robot is a new type of robot that integrates mobile robot, robotic arm and end-effector. Robotic arms and end-effectors mainly imitate the functions of human arms and hands, with emphasis on flexibility and dexterity; the mobile robot, automated guided vehiclec (AGV), imitates the walking function of human legs and feet, with emphasis on transformation and expansion of working space.

The research of composite robots in the international manufacturing power began earlier, but due to the limitations of market demand and industrial application scenarios, composite robots have not yet opened the application market. Traditional industrial robots have been able to better meet engineering applications

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for a long time, and there is no great actual demand for other new robots, resulting in the fact that composite robots have not formed an industrial application system, and only the research and development and exploration of composite robots have been carried out. As early as 1984, the German company MORO developed a composite robot system, due to the limitations of artificial intelligence technology at that time, this robot only does some simple handling. In 1994, Yamamot Company determined the ideal configuration of the robot arm with the operating degree criterion, but did not consider the mobile robot arm as a whole. In 1999, the team studied the coordination between the mobile manipulator platform and the robot arm, but did not systematically reveal the relationship between the mobility of the mobile manipulator and the maneuverability.

In 2010, with the maturity of technologies such as computer vision, laser sensors and machine learning applications, composite robots added greater flexibility and more functional scalability. Various companies launched a variety of composite robots during this period, the more typical is Kuka released KMR composite mobile robot. Later, the composite robot integrates a variety of products and technologies, such as end-execution devices with force feedback, laser or infrared sensing, visual recognition, etc., to further improve the degree of automation, such as the PR2 robot in the United States. In addition to Kuka, which has been involved in this field for a long time, the robot 'four families' including Fanuc, ABB and Yaskawa have developed composite robot-related products in recent years. In 2017, ABB Company and Guozi Mobile Robot Company launched a mobile operation robot IRB-1600, which is based on ABB's robot arm and installed on Guozi's autonomous mobility platform, and can deploy mobile stations on the robot. Yaskawa collaborated with OttoMotors to develop a path planning function that automatically generates the robot's action paths on a composite robot simulator. Fanuc partnered with Anji Intelligence to jointly launch a collaborative robot with regional mobility capabilities in 2018, combining the advantages of collaborative robots with intelligent AGV technology.

In recent years, with the new round of technological upgrading of the global manufacturing industry and the changing market demand, the world's manufacturing powers have begun the research and development and market application of composite robots. For example, in 2019, the German Aerospace Center developed a multi-machine composite robot system based on the needs of the automatic tape-laying process of composite materials for commercial aircraft, which can simultaneously deploy different numbers and widths of tow wires through pre-programmed mobile robots and robotic arms operating at designated positions, eliminating the need for cumbersome wiring and improving manufacturing capacity and flexibility. On July 20, 2021, ABB, one of the 'four families' of global robots, announced that it will acquire ASTI Mobile Robot Group and officially enter the research and development and production of composite robots. The action of industrial robot giants to open up new markets has sent a clear signal of new hot spots and new directions for the robot industry.

1.2 Main structure function of the composite robot

The composite robot mainly consists of a mobile chassis, a robotic arm, a vision system and a corresponding end effector. The LiDAR and vision module built into the mobile chassis and the end of the robot arm are the 'eyes' of the composite robot. The robot arm with the end effector enables it to have the operating ability of a 'hand', and the mobile chassis enables it to move as a whole like a 'foot' to realize the transfer and expansion of the working area. Compared with the previous single mobile chassis and robot arm, the composite robot greatly expands the reachable area of robot operation, and can be applied to more occasions without increasing the cost and deployment complexity. In particular, traditional mobile robots generally have only three degrees of freedom, industrial robot arms and collaborative robot arms have six or seven degrees of freedom, and composite robots with different end tools can have more than nine degrees of freedom.

The main structure function of the composite robot can be divided into the following four parts.

(1) Mobile: it refers to the mobile robot chassis that carries the robot's positioning, navigation, movement and obstacle avoidance functions to achieve autonomous movement. The navigation method can be divided into magnetic navigation, two-dimensional code navigation, laser simultaneous localization and mapping (SLAM) navigation, visual navigation, inertial navigation, etc. Generally, the mobile chassis uses a battery power supply and provides a power source for the entire composite robot.

(2) Execution: it refers to the robot / robot arm and end effector, through the robot arm with the end effector (claw, suction, etc.) to perform operations, generally used for material handling and unmanned operation. The robot arms are usually six or seven degrees of freedom cooperative robot arms, industrial joint robot arms, Cartesian coordinate robot arms, frog arms, SCARA robot arms, etc. In addition, according to the actual scene, the same composite robot can be

equipped with multiple robotic arms and multiple additional degrees of freedom, and the end actuator can be adopted according to the needs of the working scene.

(3) Safety: since composite robots are mostly used in man-machine mixed scene operations, safety protection devices are generally required, and safety protection devices can be designed from two aspects: a mobile chassis and a robot arm. LiDAR, electronic skin, vision sensors, ultrasonic sensors, emergency brakes, etc. are usually used on the mobile chassis to realize intelligent monitoring and identification of obstacles, autonomous safe path planning and navigation, and active safety protection. In addition, since the robot arm may work simultaneously during the movement process of the composite robot, the composite robot prefers to adopt the robot arm with high safety. Through the active adaptive compliant force position control technology of the robot arm and the passive safety force feedback adjustment technology, the safety of people, machines and objects during operation can be further ensured. Since many application scenarios of the composite robot are in the operating environment involving trade secrets, important data, etc., the information security of the composite robot is also crucial.

(4) Perception: the perception function of the composite robot is realized by various sensors, such as cameras, alarms, temperature and humidity sensors, noise sensors, gas sensors and indicators, which can perform real-time monitoring of the work site environment and automatic equipment inspection tasks, and remind the machine running status. At present, with the continuous improvement of sensor technology and the reduction of cost of industrial sensors, the design layout and data acquisition work of various sensors have become more mature. However, due to the different communication protocols and coding methods adopted by different sensor devices, there are still some difficulties in real-time data reception and processing. What needs to be improved at this stage is the ability to fuse and reprocess information from multiple sensors.

2 The key technology of composite robot

Due to the complex structure, small production batch, short update cycle, high degree of confidentiality, and variety of types of aviation products, traditional industrial robots sometimes can not meet the demand. Therefore, in the field of aviation manufacturing, composite robot technology has been gradually developed, and the demand for composite robots is increasing. Composite robots in aviation manufacturing need to better adapt to changing task requirements and complex site environments, improve positioning and movement accuracy, shorten offline programming and production preparation time, and improve equipment utilization, etc. In order to truly exploit the advantages and characteristics of composite robots, the following technologies will become the key enabling technologies of commonality.

2.1 High precision mobile robot

The two most basic parts of a composite robot are the mobile chassis and the robotic arm. Among them, as the basic equipment of composite robots, mobile robots' technology and market development have mainly experienced three important stages: the first stage is the exploration period (1978-1996), the second stage is the steady development period (1996-2012), and the third stage is the rapid development period (2012 to date). The complexity and precision requirements of aviation intelligent manufacturing make automation and intelligence a necessary choice. High-precision mobile robots can automate tasks to achieve high efficiency and consistency in the production process. Their intelligent characteristics allow them to sense, analyze and adapt to different working environments and task requirements, improving the flexibility and adaptability of the manufacturing process. In this context, the application of composite robots to the basic components of mobile robots is an effective way for mobile robots to expand their technical realization and functional added value.

The high-precision mobile robot required by the composite robot must first have a set of lightweight omnidirectional mobile chassis design for high-frequency mobile operations to meet the needs of the composite robot to operate in a complex and changing environment. The intelligent mobile chassis technology mainly includes mechanical movement, map construction, route planning and autonomous navigation. As for the form of mechanical motion, wheel type, track type, and leg type are generally used at present. In comparison, wheeled mobile robots have the advantages of small weight, large load, simple structure, relatively convenient driving and control, and fast travel speed, although the stability of movement and accurate trajectory control are greatly affected by road conditions. At present, the manufacturers of composite robots use wheeled moving chassis, which is driven by servo motor to rotate the moving wheel to realize the movement of the chassis. The construction of environment map is the key technology of mobile chassis, which is usually realized by simultaneous localization and mapping technology. Another key technology of mobile chassis is how to plan a reasonable route to the specified location based on the completed map, and how to avoid those moving obstacles when the robot moves to the target point, that is, path planning based on a known map. At present, the commonly used algorithms include Dijkstra algorithm and A * algorithm.

To achieve the effect of multi-function fusion, the composite robot itself is equipped with a variety of sensors, and the information from these sensors can be effectively used by the mobile robot and multi-sensor fusion autonomous high-precision map construction. At the same time, the high-precision chassis servo motion control technology for mobile operation is also the ability of the mobile robot required by the composite robot. On this basis, it is often easier for the mobile robot with modular design to get more comprehensive functional development on the composite robot.

2.2 High speed and high precision robotic arm

As a key technology in intelligent manufacturing, high-speed and high-precision robotic arm can improve production efficiency and capacity, reduce production costs, and improve product quality and consistency. The flexibility and safety of the robotic arm enable it to adapt to different task requirements and work environments, and by collaborating with human operators, the robotic arm realizes human-machine cooperation and improves work safety. The technology of robotic arm mainly includes motion and trajectory planning, in which the motion research of robotic arm is mainly divided into forward kinematics analysis and inverse kinematics analysis. Now, forward kinematics analysis has D-H method; but for inverse kinematics, breakthrough research and development are still needed. At the same time, the data acquisition and analysis capabilities of the robotic arm also provide important support for intelligent manufacturing and data-driven decision making. These advantages make high-speed, high-precision robotic arms indispensable for intelligent manufacturing in the aerospace industry. The robotic arm attached to the composite robot must perform efficient and accurate actions during the moving process and when arriving at the point, which is the most important support for the composite robot to realize its functions and tasks. As the composite robot has the ability to move, the working range of the robotic arm is greatly expanded, and the higher requirements for flexibility, mobility and safety of the robotic arm are also necessary.

At present, high-speed and high-precision robotic arm usually adopts impedance control to achieve compliance, but there is still a certain gap compared with real human-machine cooperation. In particular, in compliance control systems, the selection of the stability threshold is not based on proper theory and can only be determined by experience, and most systems only focus on the optimization of a single objective and few multi-objective optimization systems are studied. In order to meet the requirements of compliant control of composite robot, combined with a large number of accumulated user feedback data, it is necessary to design a multi-objective optimization adaptive control algorithm by determining the stability index, so as to realize the compliant control of high-speed and high-precision robotic arm. In summary, the robotic arm used in the composite robot also needs to complete the integrated joint design, high-speed, high-precision, multi-turn integrated joint research and development, to achieve high-speed, high-precision, flexible motion robotic arm products in the composite robot is stable and safe application.

2.3 Visual sensing and planning system

In the aviation intelligent manufacturing scenario, any part of the composite robot body can interfere with assembly personnel, products, tools, dies, etc. As a key technology in intelligent manufacturing, visual perception and planning can help robots accurately locate and identify parts, plan optimal paths and avoid obstacles, perform quality inspection and defect detection, achieve adaptive control and adjustment, and perform data analysis and optimization. These applications improve production efficiency, product quality and consistency, while increasing the flexibility and adaptability of the production line. In view of the functional diversity and scalability of the composite robot, the visual planning system should adopt a modular design method to build a hierarchical architecture of the high-precision visual perception planning system, including the core algorithm layer, the software and hardware platform layer, and the application layer. At the core algorithm level, the image processing algorithm, the recognition algorithm, and the trajectory planning algorithm are studied in depth. At the software and hardware platform level, a visual planning system is formed, including high-precision 3D cameras, vision algorithm software, and robot planning software. Planning algorithms, such as path planning or motion control, are used to make decisions and execute robot actions so that the robot can autonomously navigate, recognize targets, or perform tasks in complex environments. At the application level, visual components with different functions are formed, and the corresponding products are connected through the communication protocol defined in advance, and finally the task planning and action execution of the composite robot are guided by vision, so as to realize the more perfect application of the composite robot.

The vision perception planning system of the composite robot should have autonomous and controllable low-cost core components that can perceive the working environment of the robot arm and multi-sensor fusion perception of the target, so as to build the autonomous motion planning technology of the multi-degree of freedom robot arm under the constraints of multiple objectives. The core idea lies in combination of perception and planning, so as to enable robots to respond to a variety of real-world application scenarios in a more intelligent way.

2.4 Composite robot 'hands, feet and eyes' integrated control

As a key technology of intelligent manufacturing in aviation, the integrated control of 'hands, feet and eyes' of composite robots can realize collaborative work among robot components and improve the efficiency and quality of task execution. At the same time, the integrated control also enables the robot to have flexible work adaptability and quickly adapt to different tasks and environments. This technology also enables high-precision motion and position control, ensuring the accuracy and safety of assembly, processing and inspection in the aviation manufacturing process, which plays a decisive role in the performance of the composite robot. At present, most composite robots adopt the mode of separate control between the mobile chassis and the actuators such as the robot arm mounted on it, or communicate and coordinate multiple subsystems through the host computer without unifying multiple systems into a single control system. It is prone to result in problems such as inconsistent communication protocols, unstable communication, cumbersome programming, and insufficient intuitive operation effect of multiple robot brands. It also increases the development cost of composite robots.

With the rapid development of modern science and technology and the progress of society, the performance of composite robots is increasingly required. The research of integrated control technology of composite robots has become a new development direction in the field of composite robots. Through a series of composite robot control systems, under the premise of ensuring safety and efficiency, it can control and monitor the movement of multiple execution devices, read and process the information of multiple sensing devices. It can provide simple and comprehensive human-computer interaction functions. It can conduct joint testing and remote debugging with other composite robot devices.

To meet these high requirements, the new composite robot controller should have the following features.

(1) Open system architecture: the hardware and software architecture should be more open to meet the functions of composite robots and the needs of complex working environments.

(2) Modular subsystems: different tasks are performed by different functional subsystems, such as sensor systems, path planning systems, motion control systems, etc., to facilitate the modification, addition and configuration of functions.

(3) Real-time: the robot controller must be able to complete the corresponding computation and control tasks within a certain period of time.

(4) Network communication function: through the support of network communication functions, such as 5G, Web 3.0 and IPV6, the robot controller can achieve better human-machine collaboration, machine-to-machine collaboration ability, and can cope with more complex work scenarios.

(5) Motion control interface: EtherCAT and and CANBus interface is used to achieve real-time control of servo motor.

(6) Human, machine, environmental and data safety: the multi-in-one control system can detect the operation problems of each device of the composite robot in real time and take timely active safety measures; redundancy of computing platform and sensor hardware to provide better functional safety capabilities; multiple devices share data within the controller and are isolated from other devices to prevent important data leakage.

(7) Visual human-computer interaction interface: it is convenient for debugging personnel to debug the functions of the composite robot, task formulation and operation status monitoring.

2.5 Multi-robot collaborative operation technology

Intelligent manufacturing in the aviation industry often needs to solve complex production tasks involving large-scale production tasks. Multi-robot cooperative operation system of composite robots is the key technology to realize cluster scheduling and cooperative operation of composite robots in large-scale application scenarios. It can realize the cooperative operation of multiple robots and handle multiple tasks at the same time, thus greatly improving production efficiency. The reasonable division of tasks among different robots can achieve a highly parallel production process and shorten the production cycle. There are usually a large number of robots and tasks in the field, so how to ensure the balanced distribution and timeliness of their tasks, and how to cooperate with multiple robots to walk and work on limited paths while avoiding collisions are often the key issues.

The main technologies of multi-machine cooperative operating system include centralized robot cluster control technology, distributed robot cluster control technology and distributed perception data sharing. They include collaborative path planning and trajectory tracking, communication protocol and conflict resolution mechanism, task allocation, resource allocation, multi-machine scheduling and real-time status monitoring technology, and enable more efficient collaboration.

2.6 Safety technology of composite robot

The aviation intelligent manufacturing industry has strict safety requirements for robotic systems and must comply with relevant regulations and standards. Since the composite robot integrates the functions of a variety of original robot equipment and sensor equipment into one, and can operate and perform tasks in a wider range of space, the composite robot poses greater safety risks than the traditional robot to people in the same space, other machines and equipment, and the entire operating environment when performing tasks. In addition, the complex and diverse tasks performed by composite robots are also crucial to the management of data security during their operation. Therefore, composite robot enterprises must comprehensively consider the safety of composite robots while expanding their operational performance, and reduce safety risks while expanding functions.

For devices with strong functional integration and a large amount of data information, such as composite robots, it is necessary to focus on researching the encryption communication mechanism between robot controllers, teaching devices and programming software, the cloud edge-end secure communication mechanism of large-scale collaborative composite robot systems, and the development of a unified security bus communication architecture for composite robots. To ensure the functional scalability of the composite robot, it should support the secure access of the industrial robot arm of mainstream brands at home and abroad, and support the security monitoring and unified security management of the collected data. It supports WIFI, 2G/3G/4G/5G and other communication methods, and provides trusted data communication channels at the operator security level to ensure the safety of the robot's equipment and data transmission. A large-scale application management and control platform for composite robots should be built to support functions such as network security monitoring, work efficiency monitoring, health diagnosis and prediction of composite robots.

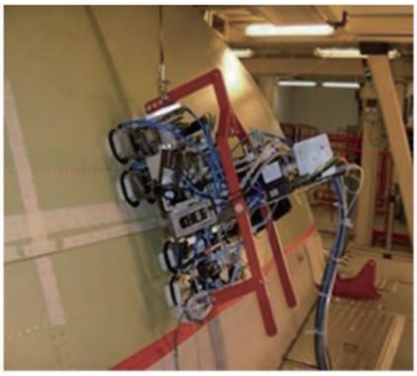
3 Application status of composite robot in aviation manufacturing

3.1 Automatic drilling and connection of aircraft

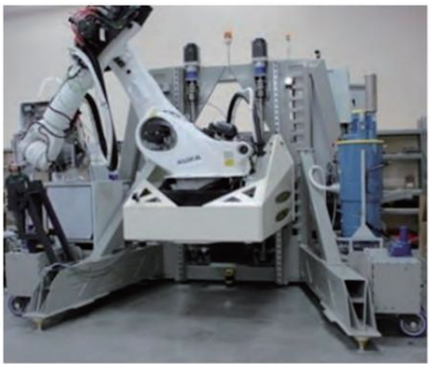
Compared with other industrial products, aircraft assembly is more manual and less automated, requiring the use of a large number of parts and joints[1]. Aircraft assembly accounts for about 40% – 50% of the total manufacturing process, and its quality directly affects the performance of the entire aircraft[2]. Riveting is currently the main joining method[3]. Good joint quality can optimize the aerodynamic layout of the aircraft and improve supersonic and stealth performance[4]. In addition, the quality of the joint also has a great impact on the life of the aircraft[5]. Data show that 70% of aircraft fatigue failures are caused by fatigue failures of structural joints, and 80% of them are caused by fatigue cracks at joint holes[6]. Therefore, the quality of the hole is very important. As aircraft structures become larger and more complex, composite robots can perform drilling and joining tasks quickly and efficiently. Compared with the traditional manual operation or the use of robots and automation equipment alone, the composite robot can realize the integration of multiple processes, meet the needs of multi-station processing, improve the accuracy of hole position, reduce the production cycle and production cost. It is gradually applied to the drilling process of large complex components in aviation.

M. Torres, a Spanish company, has developed a 5-DOF (degree of freedom) composite aerial drilling robot called TLD (Torres light drill) with eight vacuum cups (Fig. 1(a)). It can make high-precision holes for Al, Ti, CFRP and other aviation materials, the aperture error is ±0.040 mm, the socket error is ±0.050 mm and can be installed at the end of the flange over 30.000 mm. The robot also adds a visual recognition function, and can identify the reference hole to improve the accuracy of the hole position. The American company EI developed an aerial drilling robot based on AGV[7] (Fig. 1(b)). The robot is a KUKA KR500-L340 industrial robot installed on an autonomous mobile AGV, using the code tray feedback to achieve an absolute positioning error of ±0.250 mm. It has been successfully applied to high-precision drilling and sensing of the fuselage, wing, and other components[8].

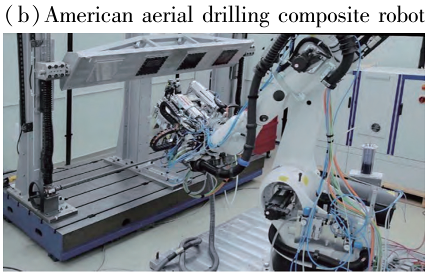
The Fraunhofer Institute for Machine Manufacturing and Automation in Germany has developed an aerial drilling robot[9] (Fig. 1(c)). The robot uses the KUKA KR210 composite robot to load the end effector and adds functions such as visual measurement, normal detection, and accuracy compensation. The average position error reaches ±0.334 mm. The average normal measurement error is ±0.290 °[10]. At the same time, the robot also has the ability of multi-sensor measurement, which can be widely used in high-precision drilling tasks in the field of aviation manufacturing.



(a) Spanish TLD aerial drilling composite robot



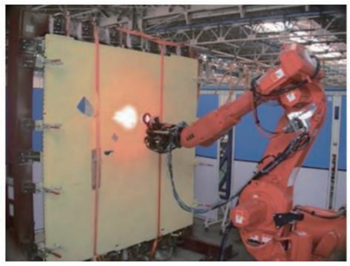
(b) American aerial drilling composite robot



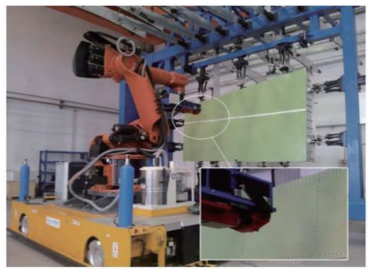
(c) German aerial drilling composite robot

Fig. 1 Foreign composite robot aerial drilling system

Domestic research on aerial drilling robots started late, but at present, many universities, aviation manufacturers and scientific research institutes have developed prototypes and conducted experiments. Among them, the composite aerial drilling robot (Fig. 2(a)) jointly developed by Professor Bi Shusheng's team at Beihang University and Shenyang Aircraft Corporation adopts a coaxial suspension form, adds a visual positioning system, and can carry out experimental research on titanium and aluminum stacked materials[11-13], achieving a positioning error of ±0.400 mm, and can complete the drilling socket in one go. The aerial drilling robot (Fig. 2(b)) developed by Zhang Yunzhi's team at AVIC Manufacturing Technology Institute realizes the operational positioning by iGPS guidance, and has been tested and verified on the C919 wing box and other components[14], which can achieve the hole position error of ±0.250 mm and the normal measurement error of ±0.250 °, and the drilling efficiency is 3 per minute[15].



(a) The aerial drilling composite robot of Beihang



(b) The aerial drilling composite robot of the AVIC Manufacturing Technology Institute

Fig. 2 Domestic composite robot aerial drilling system

Due to its advantages of flexible structure, great flexibility and large working space in the manufacturing and assembly of large aircraft parts, composite robots are gradually attracting the attention of the industry. The stable and effective automatic drilling process of composite robot is based on the study of robot system dynamics and the friction and vibration mechanism of drilling. The key technologies involved in this process is as follows.

(1) Ensure the accuracy of hole making. Modern aircraft pay more attention to the long life, stealth and interchangeability requirements of the structure, the hole position accuracy, aperture accuracy and socket depth requirements are getting higher and higher, and the traditional industrial robot positioning accuracy can reach ±0.300 mm or so, which can not meet the requirements of high hole position accuracy. The key technologies to improve the precision of hole making

are precise position servo, online fusion feedback control of multi-sensor optical vision, flutter suppression and dynamic error compensation.

(2) Multifunctional end-effector. In order to meet the requirements of hole making accuracy and surface quality, ensure processing stability, and meet the requirements of automatic hole making for tool cooling and lubrication, chip suction and discharge, and tool wear and damage monitoring, the end effector of automatic hole making system must have the functions of high-precision feed, compaction, normal vector measurement, sink depth control, drilling axial force detection, tool micro-lubrication, chip suction and processing monitoring, and so on.

3.2 Aircraft surface spraying and finishing

The spraying process is the last process in the manufacturing of aviation products, and it is also one of the most time-consuming links in the modern aviation manufacturing process. This process directly affects the appearance and performance of the product, and ensuring the thickness and uniformity of the coating is an important indicator of the spraying process[16]. The traditional spraying method requires manual operation by workers, and there are some problems such as inaccurate operation and low spraying efficiency. With the advancement of science and technology, composite robots have started to be introduced into the spraying operation. The composite robot has precise motion control and path planning capabilities to uniformly coat the entire aircraft surface, including planes, surfaces and complex geometric shapes. They can maintain a consistent coating thickness at different angles and positions, providing consistent coating quality. At the same time, compared with traditional manual operation, the use of composite robots can relieve workers from the harsh working environment, avoid harm to workers' health, and greatly improve spraying efficiency, spraying consistency, safety and environmental protection.

Lockheed Martin's robotic aircraft finishing system (RCFC) can automatically spray the F-35[17] (Fig. 3(a)), which greatly improves spraying efficiency. With the traditional manual spraying method, the B-2 bomber needs about 100 000 h and the F-22 needs about 10 000 h[18], but the automatic spraying with the composite robot can be completed in only 1 000 h, and the RCFC also expands the operational capability. The Southwest Research Institute (SwRI) has developed MR ROAM 2[19], a composite robot system for commercial or military aircraft painting missions, using Vetex's McAnham Wheel omnidirectional mobility platform, Motoman Industrial Robots, and Nikon's GPS, and has achieved a final accuracy of 0.5 inch (1 inch = 25.4 mm). It can meet the requirements of spraying applications, such as the use of inertial sensors, and the accuracy is expected to reach 1 mm or more. In addition, Carnegie Mellon University's National Robotics Engineering Center (NREC), CTC Corporation, and the Air Force Research Laboratory built a laser stripping system for military aircraft surface coatings[20] (Fig. 3(b)), which has the advantage of flexible robot assembly to adapt to different model sizes, replacing traditional mechanical friction or chemical corrosion removal methods, avoiding hazardous waste and air pollution. It also reduces labor and processing time.

(a) F-35 composite robotic aircraft finishing system

(b) Carnegie Mellon University military aircraft surface coating laser stripping system

Fig. 3 Typical spraying composite robot system

At present, there are relatively few researches on surface spraying in China, which mainly focus on the configuration and motion simulation of composite robots[21]. Many scholars have thoroughly analyzed the kinematics and dynamics of spraying robots to solve the problems of motion flexibility, workspace and unique configuration of spraying robots. Zhao et al.[22] used a robot positioner to extend the working range of the spraying robot to fully cover the spraying area of the aircraft tail, and used a laser tracker to monitor the position and spatial attitude of the aircraft. Miao et al.[23] proposed a robotic system suitable for automatic spraying of large free-form surface products (such as aircraft), introduced the mechanical structure layout and control system structure of the system, and studied the key technologies in spraying operation planning, such as aircraft pose calibration and spray gun trajectory planning, after analyzing the spraying operation process. They also developed control system software based on CATIA secondary development technology to seamlessly integrate all software operations in the painting process into the CATIA platform. Zeng et al.[24] proposed the idea of least square circular arc approximation, which ensured the spraying accuracy and effectively reduced the number of fragments of complex surfaces. Although the domestic research on surface spraying is not enough, there are many different research methods applied in this field, and these research results provide valuable support for the development of surface spraying technology.

In the face of the whole machine spraying operation of large aircraft, it is necessary to ensure the flexibility and accessibility of the working space. In order to ensure the effectiveness and integrity of the composite robot spraying operation, it is necessary to overcome the key technologies of the composite robot system. The key technologies include surface spraying path planning, fast offline programming and motion simulation technology, and accurate layer thickness prediction and control.

(1) Large-scale and complex surface spray operation planning technology. For large-scale aviation products, a composite robot is usually used as the basic spraying unit, the movement range of the robot is expanded by the displacement mechanism, the large surface is divided into blocks, and the robot is sprayed one by one. Therefore, it is necessary to study the key problems such as robot workspace analysis, surface optimal segmentation, spray trajectory overlapping between surface blocks, and robot station optimization.

(2) Fast offline programming and motion simulation technology. The production mode of one-piece and small batch of aviation products makes the operation object of composite robot change frequently, so the efficiency of robot offline programming becomes very important. Automatic trajectory planning and automatic interference check based on digital model are important means to reduce the preparation time of robot production.

(3) Accurate prediction and control of film thickness. In order to achieve good coating uniformity, it is necessary to conduct a large number of repeated spray tests in advance to determine the spray trajectory and process parameters. The in-depth study of the factors affecting the film thickness distribution, the establishment of a more accurate spray gun model, and the realization of numerical simulation of the spraying process have very important guidance significance for accurately predicting and controlling the film thickness, improving the spraying quality, and reducing the times for repainting/polishing the product.

3.3 Parts handling and assembly

With the continuous development of science, technology and the vigorous development of manufacturing industry, traditional handling robots can not meet the current production demand[25]. Therefore, It is needed to enrich the functions of handling robots through innovative research and development. As an integral part of the aircraft flexible assembly system, the composite robot has multi-axis freedom and programmability to adapt to different types and shapes of parts. It can perform precise gripping, picking, moving and placing operations to adapt to different handling needs. The composite robot can also replace tools and fixtures as needed to achieve flexible conversion of a variety of handling tasks. There are two main applications[26]: one is the use of composite robots to achieve a wide range of handling, usually using line patrol, indoor GPS and other navigation technology to quickly and accurately arrive at the designated position and transport product components to the target location; the other is to achieve precise handling and positioning of a small range of parts. The common method is to combine high-precision measurement equipment and composite robots, set key measurement points on the workpiece, use high-precision measurement equipment to monitor its motion state and attitude. And according to the calculated motion trajectory, the robot will be assembled workpiece moved to the correct position.

In the field of aviation assembly, there are many large parts, and the composite robot has a wide application prospect in the long-distance transportation of aviation large parts. Foreign automation companies such as EGEMIN, AXTER, KUKA and FORI have developed many technologies related to the transportation of large parts. For example, the D-NOSE component of the Boeing 787 is handled robotically on the drilling and riveting machine. KUKA's OmniMove omni-mobility system (Fig. 4(a)) was used by Austrian Airlines to replace aircraft engines, reducing the operation time from 16 h to 5 h and allowing movement accuracy up to millimeters. Li[27] of Shanghai Jiao Tong University developed an integrated assembly system for load shifting and docking based on the cooperation of multiple positioning tools (Fig. 4(b)). Using hybrid force and position control, formation coordination algorithm, and indoor navigation technology, autonomous handling and automatic attitude adjustment of simulated wing components of large passenger aircraft are realized. China Third Aerospace Science and Technology Corporation and other units have also successfully developed systems suitable for aviation assembly production lines, greatly improving the handling efficiency and production flexibility of large components in aviation assembly (Fig. 4(c)). The application of these technologies reflects the important position of composite robots in the manufacturing industry, and is expected to play a great role in the future[28-30].

(a) KUKA composite robot handling platform

(b) Shanghai Jiao Tong University multi-compound robot cooperative handling diagram

(c) China Third Aerospace Science and Technology Corporation large component assembly composite robot

Fig. 4 Composite robot system applied to aviation component handling

Different from the guideway mobile robot system, the composite robot integrated with AGV realizes the functions of large part handling and assembly attitude adjustment. It is needed to pay attention to the key performance indicators such as omnidirectional body movement, load and three-dimensional attitude adjustment accuracy. The key technologies involved in this process include:

(1) Virtual simulation technology. The environment of aircraft assembly station is complex and not spacious, so it is necessary to conduct simulation before operation to avoid interference collision that may occur during physical assembly, saving time and improving operation safety.

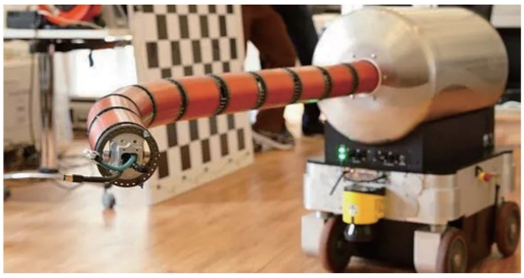
(2) Real-time feedback during assembly. It mainly refers to the position feedback and force feedback, where the position feedback is the use of visual sensors to monitor the position between the installed parts and the peripheral equipment or the assembly matrix in real time to avoid accidents; the force feedback is to use the force sensor to monitor the contact state between the installed parts in real time to achieve active and passive flexible assembly.

(3) Digital assembly line. The further integration of the composite robot into a relatively complete digital production line, which can be used for aircraft assembly or final assembly, is a sign of the advanced technology of modern aircraft manufacturing and a brilliant market selling point.

3.4 Aircraft measurement and inspection

In the aircraft manufacturing process, various performance parameters need to be tested on different parts to ensure overall performance. The composite robot has multi-axis freedom and a flexible working end that can measure and sense in multiple dimensions. It can adapt to complex aircraft geometry and perform 3D measurements, surface measurements and other complex shape measurement tasks. By installing a measuring head at the end of the composite robot and setting a detection point, a robot detection system[31] can be built, which can be used to detect various performance parameters of the aircraft without detection duplication or omission, to ensure that the overall performance of the aircraft meets the requirements of use. Compared with the traditional detection system, the composite robot detection system has the characteristics of good flexibility and high repeatability, avoids the shortcomings of the traditional sensor support axis, and saves the space and labor.

Automatic detection equipment is a crucial link in the aviation assembly process by detecting key information to ensure assembly quality[32]. At present, composite robot inspection has been applied to aperture measurement, shape inspection, and non-destructive inspection. OC Robotics, a British company, installs a snake-like robot arm (Fig. 5(a)) at the end of the composite robot to solve the problem of difficult access to the aircraft inspection environment, to complete the inspection, fastening, sealing, and other operations[33]. Wang[34] of Hefei University of Technology designed a series of non-destructive testing systems by using a composite robot (Fig. 5(b)). The system consists of the carrying platform, robot arm, ultrasonic phased array testing equipment at the end, and so on. The system can realize fast, efficient and non-destructive testing through the cooperative movement of AGV and robotic arm, and has been successfully applied to the automatic non-destructive testing of large aircraft wing skin.



(a) OC Robotics' serpentine arm composite robot

(b) Composite robot nondestructive testing system

Fig. 5 Composite robot automatic detection system

At present, the composite robot has a broad application prospect in the automatic inspection of large parts in aviation. The participation of the composite robot in the automatic detection process can speed up the refinement of the detection process, improve the detection efficiency and credibility, and provide accurate pose for the inspection execution equipment. However, the relative position between the large parts and the mobile platform is difficult to monitor in real time, and its spatial positioning accuracy affects the accuracy of the entire machining and assembly, which directly affects the dynamic shape of the aircraft. In order to improve the machining and assembly accuracy of aircraft parts, the selection of composite robots should fully consider the actual task scenarios and accuracy requirements of pulsating stations, and coordinate the contradictions between system flexibility and measurement accuracy[35]. Key technologies involved in this process include:

(1) Dynamic position accuracy compensation technology based on optical measurement system. This paper studies the method of establishing and converting the coordinate system required by tool coordinate system, workpiece coordinate system, camera coordinate system, robot coordinate system, world coordinate system, etc., to detect and control the position of composite robot end and moving platform in real time, and provide precision compensation scheme for optical measurement system.

(2) Area segmentation measurement technology based on vision. In order to determine the relative position relationship between the mobile platform and the large parts, it is often necessary to use visual means to detect the surface of the large parts, and then realize the positioning of the mobile robot machining system. However, due to the large size of large aircraft components, many features to be measured, and high measurement accuracy requirements, the existing detection technology can not support one-time measurement, and usually adopts multiple area segmentation measurement, and the measurement data is splicing.

4 Future innovative development trends of composite robots

4.1 Standardization of composite robot

The field of aviation intelligent manufacturing will pay more attention to the standardization of composite robots. Standardization can promote interoperability and compatibility among different robot systems and improve the efficiency of system integration. The development of a unified standard can ensure the safety and reliability of robots in various scenarios. At present, the composite robot companies in the market are basically dominated by mobile robot manufacturers, and the cooperative development is generally dominated by mobile robot manufacturers. In the process of joint development, because the interface of mobile robot chassis and industrial robotic arm is not the same, the robotic arm manufacturer should make adaptive design according to the needs of chassis manufacturer. In addition to the different interfaces between the robotic arm and the chassis, the interfaces of different robotic arm manufacturers are also different, which is the main problem faced by the current mobile robot in procuring robotic arms from different manufacturers. At the same time, different robot arm manufacturers have their own systems, the use of methods and functions are different, which brings some problems to the development of composite robots.

At present, the application development ecology of composite mobile robots is relatively closed. The composite mobile robot can not meet the rich and diversified application scenarios and requirements. Therefore, the model of composite mobile robot application development should be similar to the IT field——through standardization and openness, reducing the development threshold, so that more people can participate in the process of application design and development. As part of the standardization of composite robots, the universal capabilities of sensing, grasping, and moving are expected to become the core software and capability modules in the future development environment, allowing developers to quickly configure and invoke them at any time, like calling application programming interfaces (APIs).

4.2 The integration development of '5G + cloud computing + AI' and composite robots

The rapid development of technologies such as '5G + cloud + AI', resource sharing, knowledge sharing, data mining and other concepts provides new ideas for improving the analysis, decision-making and collaboration capabilities of composite robots in aviation intelligent manufacturing scenarios. Due to its high speed, low latency, cloud intelligence, and massive connectivity, 5G technology has attracted much attention and is considered as a 'booster' for the realization of the Industrial Internet, which can provide a stable network foundation for the Industrial Internet and support data transmission and communication among various intelligent devices[36]. In addition, the emergence of cloud computing also solves the problem of traditional applications becoming more complex. Compared with the traditional single human replacement robot in specific work scenarios, the composite robot faces a wider range of work scenarios, has deeper interaction with humans, and has higher flexible adaptability to the composite robot. By combining technological adventages such as 5G, cloud service, and artificial intelligence (AI), robot application functions are deployed in the cloud. The robot background maintenance is performed by the cloud. It can easily realize flexible deployment of service robots in different work environments to meet the needs of different enterprises and scenarios[37]. As a result, the integration of these technologies will further improve data transmission and communication capabilities for more efficient, precise, and sustainable aviation manufacturing, and facilitate the upgrading of composite robots in various ways.

(1) High-speed data transfer and real-time communication. The application of 5G technology will achieve high-speed data transmission and real-time communication capabilities, providing a more stable and reliable network connection for composite robots. This will enable robots to collect and share data in real time, improve decision-making and response speed, and further enhance production efficiency and quality.

(2) Cloud platform and big data analytics. The use of cloud platforms will provide large-scale data storage and processing capabilities for intelligent manufacturing in aviation. The composite robot can upload the collected data to the cloud platform for analysis and learning, to achieve intelligent decision-making and optimization. Big data analytics technology can mine the hidden information in the data to provide more accurate predictions and optimization recommendations for aviation manufacturing processes.

(3) Artificial intelligence and machine learning. AI and machine learning technologies will play a key role in intelligent manufacturing in the aviation industry. Through AI technology, composite robots can realize autonomous perception, autonomous decision making and autonomous learning, and improve the degree of automation and intelligence of work. Machine learning algorithms can provide more accurate prediction and optimization models by learning from historical data.

(4) Autonomous collaboration. Collaboration among composite robots will be more autonomous and efficient. Robots can coordinate and communicate through the cloud platform to jointly solve complex tasks. Using AI technology, robots can independently plan and coordinate actions, achieve a higher level of task division and collaborative work, and improve production efficiency and quality.

(5) Intelligent safety and fault diagnosis. The composite robot system that integrates '5G, cloud and AI' will have a higher level of security and fault diagnosis capabilities. The robot can monitor and analyze the status of the system in real time, predict potential failures, and take appropriate actions. In addition, through the network connection, the robot can achieve remote monitoring and operation with the monitoring system, ensuring the safety and stability of the aviation intelligent manufacturing process.

4.3 Integrated development of intelligent sensors and composite robots

The integration and development of intelligent sensors and composite robots is an important trend in the field of intelligent manufacturing in aviation. Through improved sensing capability, multimodal sensor fusion, enhanced data processing and decision-making ability, improved adaptability and learning ability, and networking and cloud support, composite robots can achieve more advanced intelligence and autonomy. In addition, innovation and development in the field of aviation intelligent manufacturing should be promoted.

(1) Environmental awareness and positioning: the application of smart sensors can help composite robots achieve high-precision environmental awareness and positioning capabilities. By using sensors such as liDAR, vision sensors, and inertial navigation systems,

the robot can sense surrounding obstacles, measure the position and attitude of the workpiece, and accurately position itself. This is critical for fine manipulation and collision avoidance in the complex aviation manufacturing environment.

(2) Adaptive control and optimization: real-time data generated by intelligent sensors can be used to achieve adaptive control and optimization of composite robots. The robot can adjust its actions and strategies in real time based on sensor data to adapt to different working conditions and environmental changes. Through optimization algorithms and data analysis, robots can automatically adjust parameters and paths to improve production efficiency and quality.

(3) Human-machine collaboration and safety: the application of smart sensors can achieve human-machine collaboration and safety. Through real-time monitoring by sensors, the composite robot can sense the presence and movements of a human operator, enabling it to work safely with humans. In addition, sensors can also monitor risk factors in the work environment, such as high temperature, high pressure, and take appropriate measures to ensure the safety of operators and equipment.

(4) Data-driven decision making and optimization: large amounts of data generated by smart sensors can be mined and analyzed through data analytics and machine learning techniques to support decision-making and optimization of composite robots. By analyzing sensor data, robots can predict and identify potential problems, and make adjustment and optimization accordingly, improving production efficiency and product quality.

5 Conclusions

This paper introduces the key technology of composite robot and the application research example of composite robot in aviation intelligent manufacturing. It analyses the safety, high efficiency and easy-to-use characteristics of composite robot and its application prospect in aviation intelligent manufacturing. At present, the composite robot industry is developing rapidly, but the threshold of composite robot technology is high. The existing application of composite robot in aviation manufacturing is in the application exploration stage. The real industrial application needs to be combined with the manufacturing process and production site conditions for in-depth and detailed application development to meet the actual production needs. With the full spread of intelligent manufacturing projects such as aircraft pulsating production lines, the future factory characterized by intelligent planning and decision-making and digital twin technology has begun to emerge. The research of future collaborative robots should explore theoretical methods and technologies to improve the cognitive ability and autonomous operation ability of composite robots on the basis of strengthening safety assurance and efficiency. The composite robot will not only become a tool to reduce the labor intensity of workers and improve the operating ability of the process, but also reduce the technical level requirements of workers and better perform the complex tasks under complex working conditions. The composite robot will work together with traditional industrial robots and automation equipment to improve the quality, efficiency and flexibility of aviation intelligent manufacturing. It will give new impetus to the leapfrog development of aviation manufacturing, and bring new application value to the robotics field.

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