Journal of Computing and Electronic Information Management
ISSN: 2413-1660 | Vol. 14, No. 1, 2024

Application Progress of Robot Precision Compensation Technology in Aviation Manufacturing

Nan Xiao

Mechanical Engineering, North Carolina State University, Raleigh, North Carolina, USA
m15920892215@gmail.com

Abstract: With the increasing demand for product quality and precision in aviation manufacturing industry, the application of robot technology in this field is more and more extensive. However, the accuracy of robot operation has always been a key factor restricting its application. This paper summarizes the research progress of robot precision compensation technology in the field of aviation manufacturing in recent years. This paper first introduces the application status of robot technology in aviation manufacturing, and then analyzes the principles of various precision compensation technologies and their application examples in aviation manufacturing. Through the analysis and summary of the research content, through reasonable precision compensation technology, the operation precision of the robot can be significantly improved, thus meeting the high precision requirements of aviation manufacturing. This paper also analyzes the challenges of robot precision compensation technology in aviation manufacturing field, and looks forward to the application prospect of precision compensation technology in aviation manufacturing field, which provides valuable reference for researchers and enterprises in related fields.

Keywords: Robot; Accuracy compensation; Aviation manufacturing; Application progress.

1. Introduction

Aviation manufacturing industry embodies a country's comprehensive national strength and is a strategic industry related to national economic construction and national defense security. With the development of new aircraft models such as large aircraft and fourth-generation aircraft in China entering a new stage, the requirements of aviation manufacturing industry for high quality, high efficiency and long life are getting higher and higher, and it has become an inevitable trend to realize digitalization, flexibility and intelligence of aircraft manufacturing (Li,2023). However, in practical application, due to the structural limitations of the robot itself, the imperfection of the control system and external environmental factors, its operating accuracy is often difficult to meet the standards of aviation manufacturing. At the same time, with the increasing complexity of aircraft structure and the increasing demand for lightweight, traditional processing methods have been difficult to meet the needs of modern aviation manufacturing. Robot precision compensation technology came into being and became the key means to improve robot operation precision. This technology can significantly reduce the positioning error and repeated positioning error of the robot by real-time detection and compensation of the errors during the robot movement, thus improving its operation accuracy (Zhou, 2012). In the field of aviation manufacturing, the application of precision compensation technology not only helps to improve product quality, but also significantly improves production efficiency and reduces manufacturing costs, thus promoting the progress and development of the entire aviation manufacturing industry. With the expansion and deepening of robot application, industrial robots begin to enter some high-precision manufacturing fields, such as aircraft assembly, laser cutting, flexible grinding and so on. Boeing, Airbus, Lockheed Martin, NASA and other world aerospace giants have adopted flexible manufacturing technology and equipment with robots as the core as an effective new way to solve the above problems, as shown in Figure 1. Under the background of China's vigorous development of aerospace industry, it is of great significance to build flexible manufacturing units or flexible production lines based on industrial robots to realize rapid, flexible and automatic production of products, which will transform and upgrade the production mode of aerospace manufacturing industry, improve equipment manufacturing capacity and product performance. This paper aims at summarizing the application progress of robot precision compensation technology in aviation manufacturing, analyzing the application status of various compensation technologies, and discussing their challenges and prospects in practical application. Through in-depth research and analysis, it aims to provide theoretical support and practical guidance for the application of robot technology in aviation manufacturing industry and promote the sustainable development and innovation of aviation manufacturing industry.

2. Principle of robot precision compensation technology.

2.1. Main principles

The principle of robot precision compensation technology is to identify and analyze the robot's operation errors by monitoring the robot's posture, trajectory and other information in real time, and then use compensation algorithm to compensate the errors, so as to improve the robot's operation accuracy (Liao et al. 2022). The principle of robot precision compensation technology is mainly based on the comprehensive consideration of robot kinematics, dynamics and sensor technology. Its core goal is to identify, model and compensate the motion error of the robot by various means, so as to improve the positioning accuracy and repetitive positioning accuracy of the robot.

2.2. Compensation methods

Robot precision compensation technology can be divided into two categories: off-line error compensation method and on-line error compensation method.

(1) Offline error compensation method

This method mainly compensates the positioning error by establishing a real kinematic model or an error model before the robot works (Wang et al. 2022). According to the different calibration methods of robot model, offline compensation methods can be subdivided into kinematic model calibration, non-model calibration and robot self-calibration according to their calibration principles or measurement methods, and their specific introduction is shown in Table 1. The calibration method of kinematic model is to calibrate the real kinematic model by identifying the kinematic parameter error through the parameter identification algorithm after obtaining the actual pose error by certain measuring means.

Figure 1. Robot automatic drilling (aircraft assembly)

Table 1. Offline Compensation Methods and Principles

Classification	Chief method	Principle
Kinematic model calibration	Kinematic model calibration mainly depends on the kinematic model of the robot, and the geometric parameters of the robot are optimized through accurate measurement and calibration.	The kinematics model of the robot describes the geometric relationship between each joint of the robot and the end effector. By collecting the terminal pose data of the robot under different joint configurations, and using the optimization algorithm to solve the parameters of the robot model, the predicted pose of the model is as close as possible to the actual measured value.
Non-model calibration	Model-free calibration does not depend on the kinematic model of the robot, but directly measures the terminal pose of the robot by using external equipment (such as laser tracker and vision system).	The external equipment provides the actual pose information of the robot. By comparing with the theoretical pose in the robot controller, the error can be calculated and compensated. This method does not depend on the internal model of the robot, so it is not affected by the model error.
Robot self-calibration	Robot self-calibration uses the information of the robot's own sensors and actuators to realize the self-calibration of robot parameters through specific trajectory planning or autonomous motion.	By planning the specific trajectory of the robot and monitoring the data of the end effector or internal sensor of the robot, the internal parameters of the robot can be estimated. This method does not need external equipment, and completely depends on the robot's own perception and control ability.

Yin (2015) considered that there are many factors that affect the absolute positioning accuracy of industrial robots, and proposed a method of grading compensation for different types of error factors. Aiming at joint error factors, joint error classification compensation is adopted; Aiming at the geometric error factors, the method of geometric error modeling and calibration is adopted. Aiming at the non-geometric error factors, a compensation method based on joint space grid segmentation is adopted. Improve the absolute positioning accuracy of the robot to the level of repeated positioning accuracy. Because the repeated positioning accuracy is determined by the random original error, and the absolute positioning accuracy is determined by the deterministic original error, theoretically, in the off-line compensation method, the upper limit of the robot absolute positioning accuracy compensation is the repeated positioning accuracy.

(2) Online error compensation method

In this method, real-time feedback devices, such as three-coordinate measuring instrument, laser tracker, club instrument and other external detection devices, are usually attached to the joint axis or end effector of the robot, and the joint angle or end pose is obtained in real time and input into the controller for feedback correction control, thus ensuring the positioning accuracy of the robot (Wang et al. 2022). Typical applications include K-series optical coordinate measuring machine (OCMM) produced by KUKA Company of Germany in cooperation with Nikon to realize real-time correction of robot end positioning and real-time positioning compensation of Airbus production line workpiece.

According to different control links, online error compensation methods can be divided into semi-closed loop compensation and full closed loop compensation. Full-closed-loop compensation is to measure the position and posture of the robot end in real time through external instruments and feed it back to the robot control system, so that the robot can adjust its current state, thus achieving the corresponding positioning accuracy and posture requirements.

Shi et al. (2017) skillfully combined the laser tracker with the Robot Sensor Interface (RSI) provided by KUKA robot, and successfully realized the closed-loop control online compensation of robot pose error. This innovative method significantly improves the absolute positioning accuracy of the robot, and the improvement range is close to an order of magnitude. What's more, this compensation mechanism is excellent in real-time, and can quickly deal with the errors caused by the internal and external factors of the robot without complicated calculation, thus ensuring the accuracy and stability of the robot operation. The specific operation process is shown in Figure 2:

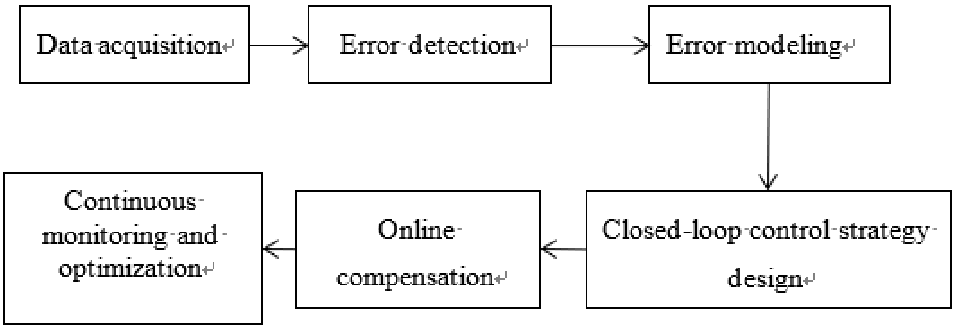

Figure 2. On-line compensation process of robot pose error by closed-loop control.

3. Application status of robot precision compensation technology in aviation manufacturing field.

The application status of robot precision compensation technology in the field of aviation manufacturing is mainly reflected in the precision machining and assembly of the structural parts of super-large aircraft. In the field of aviation manufacturing, the application of robot accuracy compensation technology mainly includes the following parts:

3.1. Robot system

Robot system is the basis of precision compensation, which needs to have high precision, high rigidity and high stability. At the same time, the robot system also needs to be equipped with various sensors, such as force sensors, displacement sensors, etc., to obtain the motion state of the robot and all kinds of information in the machining process in real time. Gao et al. (2001) designed a signal processing method for a six-dimensional force sensor for the special needs of space robots, which improved its measurement accuracy and stability and provided strong support for the accurate control and operation of space robots. He (2013) realized the real-time monitoring and accurate measurement of the robot drilling and riveting process through the integration of various sensors, improved the drilling and riveting quality and efficiency, and made contributions to the development of the field of robot automatic processing. Zhu et al. (2018) used the binocular stereo vision system to monitor the temperature change of industrial robots in real time, and adjusted the robot's motion trajectory through the compensation algorithm, thus achieving accurate control under high temperature environment and improving the working performance of industrial robots. Shen et al. (2023) accurately controlled the grasping position of the robot through the precise positioning algorithm based on the vision sensor, which improved the accuracy and efficiency of the robot's grasping. By means of experimental error investigation and modular compensation, Schneider et al. (2016) reduced the influence of error on machining accuracy during robot machining and improved the stability and reliability of robot machining. By using binocular vision measurement and deep belief network (DBN), Wang et al. (2021) realized the accurate measurement and compensation of the attitude of mobile industrial robots, improved the accuracy and stability of the attitude, and provided guarantee for the operation of robots in complex environments. Ma et al. (2018) used intelligent trajectory sensors to model and compensate kinematic errors of industrial robots, improve motion accuracy and stability, and provide an effective means for precise control of robots.

3.2. Precision compensation module

The precision compensation module is the core part of precision compensation, which is mainly responsible for identifying, modeling and compensating the motion error of the robot. Accuracy compensation module usually includes error identification algorithm, error modeling algorithm and compensation control algorithm. Hong et al. (2015) proposed an error compensation method based on spatial meshing. By constructing a spatial grid model, the errors in the robot motion process can be detected and compensated in real time, and the compensation parameters can be dynamically adjusted according to the error changes in different positions. Sun et al. (2019) proposed a robot precision compensation method based on approximation weighted average interpolation method. By calculating the approximation of each joint of the robot, weighted average interpolation method was used to compensate the error, which could effectively reduce the motion error of the robot in a complex environment and improve the working accuracy of the robot. Zheng (2019) designed a two-level feedback system to monitor the robot's motion error in real time and feed the error information back to the control system for compensation, which can realize rapid response and accurate compensation of the robot's motion error and improve the robot's operational stability and accuracy. Feng et al. (2019) combined particle swarm optimization algorithm and extreme learning machine to build a new robot accuracy compensation model, which can quickly converge to the optimal solution and realize efficient compensation for robot errors. Nguyen et al. (2022) proposed an analytical model considering the uncertainty of joint stiffness to compensate the errors of robotic end-effectors during milling, effectively improving the accuracy and stability of robotic end-effectors. Bo et al. (2022) used the neural network model to predict and compensate the positioning errors of industrial robots, effectively improving the positioning accuracy and stability of industrial robots. Yuan et al. (2018) used the extreme learning machine algorithm to quickly learn and compensate the errors of the aerial drilling robot during its movement, which significantly improved the absolute position accuracy of the aerial drilling robot. Finally, Wang et al. (2020) used a real-time laser tracker to compensate the errors in robot drilling and processing in real time, realizing accurate control of robot motion errors and improving the accuracy and efficiency of robot drilling and processing.

3.3. Machine vision system

Machine vision system is more and more widely used in the field of aviation manufacturing, and it can be used to accurately locate and identify aircraft structural parts. Through the integration with the robot system, the machine vision system can provide real-time position and attitude information for the precision compensation module, and help the robot to realize more accurate machining and assembly. Liu et al. (2017) designed a remote control assembly system based on machine vision to achieve accurate assembly of the remote control. Wang et al. (2020), on the other hand, studied the error compensation method in the assembly process of wafer components to improve the assembly accuracy and quality. Jiang (2016) proposed a pose estimation-oriented camera system calibration method to improve the measurement accuracy and stability of machine vision systems. Yang et al. (2014) improved the calibration method of the robot flexible vision measurement system to improve the accuracy and stability of the vision measurement system. Lopez et al. (2008) explored different approaches and limitations of machine vision and provided useful references for the development of machine vision technology. Finally, Kong &Yu (2022) proposed an error compensation method based on machine learning to improve the motion accuracy of industrial robots, while Zhu et al. (2014) analyzed the error sources of the two-dimensional vision system of robot drilling and proposed a method to improve the accuracy..

3.4. Automated assembly line

Automatic assembly line is an important part in the field of aviation manufacturing, which can realize the automatic assembly of aircraft structural parts. By combining with robot precision compensation technology, the assembly precision and efficiency can be greatly improved. Zhou. (2012) studied the spatial grid accuracy compensation method of robot for aircraft automatic assembly. They put forward an error compensation strategy based on spatial grid. By constructing the error model in the process of aircraft assembly, the trajectory of the robot can be adjusted in real time to achieve high-precision aircraft assembly. This research provides an effective means for improving the accuracy of aircraft automatic assembly. Li (2012) designed a six-axis CNC aircraft assembly drilling and milling machine in his doctoral thesis, and studied its error compensation method. He analyzed the error sources of the drilling and milling machine in the process of aircraft assembly, and put forward the corresponding compensation strategy to improve the assembly accuracy. This research is of great significance for improving the quality and efficiency of aircraft assembly. Lu et al. (2020) studied the visual positioning guidance system for automatic precision assembly. They use machine vision technology to achieve accurate positioning of assembly parts, and control the trajectory of the robot through the guidance system to achieve high-precision assembly. This research is of great significance to improve the accuracy and stability of automatic assembly. Liu et al. (2018) studied the robot precision compensation technology based on mechanical joint feedback. They adjust the robot's motion trajectory in real time by analyzing the robot's mechanical joint motion data to compensate the assembly error caused by joint error. This research provides a new idea and method for robot precision compensation. Jiang et al. (2016) proposed an on-line compensation method, which was used in the robot measurement integration system with high precision assembly. By monitoring the motion data of the robot in real time, they can compensate the errors in the assembly process in real time to improve the assembly accuracy. This research provides a new solution for robot high-precision assembly. Drouot et al. (2018) studied the measurement-aided high-precision aerospace manufacturing assembly technology. They use advanced measurement technology to monitor the errors in the assembly process in real time, and compensate the errors through feedback control system to realize high-precision aerospace manufacturing assembly. This research is conducive to improving the quality and performance of aerospace products.

4. The challenge of robot precision compensation technology in the field of aviation manufacturing.

4.1. Influence of dynamic environment on robot precision compensation

In the field of aviation manufacturing, robot precision compensation technology faces many challenges. Among them, the influence of dynamic environment on robot precision compensation is particularly significant. Because the aviation manufacturing process involves a variety of complex equipment and technological processes, the changes of these equipment and technological processes will have a dynamic impact on the robot working environment, such as temperature fluctuations, vibration interference and so on. These factors may lead to the deviation of the robot trajectory, thus affecting the assembly accuracy (Li et al,2007). Taking aircraft wing assembly as an example, the vibration and temperature changes caused by the simultaneous operation of several large-scale equipment at the assembly site have seriously affected the working environment of the robot. In actual operation, the robot often appears trajectory deviation due to environmental interference, which leads to the assembly accuracy is not up to standard. In order to solve this problem, the technical team introduced advanced vibration and temperature monitoring equipment to monitor and adjust the robot's trajectory in real time, thus effectively reducing the impact of environmental interference on robot precision compensation.

4.2. Real-time monitoring of robot trajectory

Real-time monitoring of robot trajectory is also an important challenge for precision compensation technology. In the process of aviation manufacturing, real-time monitoring of robot trajectory is the key to ensure the assembly accuracy (Zhang ,2019). Because the assembly of aircraft engine involves many high-precision components and strict assembly sequence, any tiny trajectory deviation may lead to assembly failure or product quality problems. Therefore, it is very important to monitor the trajectory of the robot in real time. In order to achieve this goal, technical teams usually adopt high-precision sensors and data processing technology. These sensors can monitor the displacement and stress of the robot in real time, and provide real-time feedback about the actual motion state of the robot for technicians. However, in the actual operation of aircraft engine assembly, the technical team found that the robot is prone to trajectory deviation in some specific positions. There may be many reasons for this deviation, such as the flexibility of robot joints, external interference during assembly and environmental temperature changes. These factors may affect the trajectory of the robot, leading to trajectory deviation. In order to solve this problem, the technical team optimized the robot trajectory planning algorithm. According to the real-time monitoring data, they accurately adjusted the trajectory of the robot to eliminate the potential trajectory deviation. In addition, the technical team has taken other measures, such as strengthening the rigidity of the robot, reducing external interference during assembly and controlling the ambient temperature, to improve the accuracy and stability of the robot's motion trajectory.

4.3. Calculation and Implementation of Precision Compensation Technology

Precision compensation technology plays a vital role in aviation manufacturing, and its calculation and implementation process are full of challenges. In order to ensure the high-precision assembly of aircraft components, the technical team must deeply study and apply advanced compensation algorithms and control technologies. They not only need to have a solid theoretical foundation and rich practical experience, but also need high-performance computers and advanced control systems to realize efficient operation and precise control of the algorithm (Liao et al., 2022). Taking the aircraft landing gear assembly as an example, the technical team first established the kinematics model and error model of the robot accurately, which is the cornerstone of precision compensation. Subsequently, they designed a compensation algorithm based on the least square method, which can accurately identify and correct the errors in the assembly process. In practice, the application of high-performance computer enables the compensation algorithm to be calculated quickly, ensuring the real-time and accuracy of compensation. At the same time, through the advanced control system, the compensation results can be applied to the trajectory adjustment of the robot in real time. After many experiments and optimization, the technical team successfully achieved high-precision landing gear assembly. This not only shows the practical application value of precision compensation technology in aviation manufacturing, but also highlights the professional ability and innovative spirit of the technical team in the face of challenges.

5. Prospect of robot precision compensation technology in aviation manufacturing field.

5.1. Development trend of adaptive and intelligent precision compensation technology

With the rapid progress of science and technology, robot precision compensation technology is welcoming a brand-new development stage-adaptation and intelligence. The future precision compensation technology will no longer be a simple fixed parameter adjustment, but will move towards a highly adaptive and intelligent direction. This means that the robot will be able to dynamically adjust the compensation strategy according to the real-time environmental changes, task requirements and its own state, and realize a more accurate and efficient assembly process (Kumar& Srinivas, 2019). Intelligent precision compensation technology will combine artificial intelligence, machine learning and other advanced technologies to make the robot have the ability of self-learning and self-optimization. Through the accumulated data and experience, the robot can continuously optimize its accuracy compensation algorithm and improve the assembly accuracy and efficiency. At the same time, with the development of cloud computing, big data and other technologies, robot precision compensation technology will be able to achieve more efficient data processing and analysis, providing strong support for the development of intelligence.

5.2. Development of intelligent robot and its application prospect in aviation manufacturing field

As an important representative of modern manufacturing industry, intelligent robot is showing broad application prospects in the field of aviation manufacturing with its characteristics of high efficiency, accuracy and flexibility. With the continuous development of artificial intelligence, machine learning and other technologies, intelligent robots will be more powerful and can adapt to more complex and changeable manufacturing environment. In the field of aviation manufacturing, intelligent robots will be able to undertake more high-precision and high-efficiency assembly tasks, such as precise docking of aircraft parts and welding of complex structures (French et al., 2019). In addition, intelligent robots can also work closely with human workers to complete some complex manufacturing tasks and improve the overall production efficiency and quality. At the same time, with the popularization of technologies such as 5G and Internet of Things, intelligent robots will be able to realize more efficient information transmission and collaborative work, and further improve the intelligent level of aviation manufacturing. It can be said that intelligent robots will become an important supporting force in the future aviation manufacturing field and promote the aviation manufacturing industry to a higher level.

6. Conclusion

In conclusion, the application of robot precision compensation technology in the field of aviation manufacturing has achieved remarkable results, which can not only improve production efficiency, but also significantly improve product quality. Through real-time monitoring and calculation, the robot can accurately perform complex manufacturing tasks, thus reducing the errors and uncertainties caused by human operation. In addition, the application status of robot precision compensation technology in the field of aviation manufacturing is mainly reflected in its precision machining and assembly of super-large aircraft structural parts. By constructing a complete framework including robot system, precision compensation module, machine vision system and automatic assembly line, high-precision and efficient processing and assembly of aircraft structural parts can be realized, which provides strong support for the development of aviation manufacturing field. However, it must also be recognized that this technology still faces many challenges, such as dynamic environmental interference, research and development of high-precision sensors and algorithms. Therefore, we need continuous exploration and innovation to overcome these challenges and promote the continuous development of robot precision compensation technology. Looking forward to the future, with the advent of the era of intelligent manufacturing, robot precision compensation technology will become one of the indispensable core technologies in the field of aviation manufacturing, providing strong support for the rapid development and upgrading of aviation industry.

References

[1] Bo, L. I., Wei, T. I. A. N., Zhang, C., Fangfang, H. U. A., Guangyu, C. U. I., & Yufei, L. I. (2022). Positioning error compensation of an industrial robot using neural networks and experimental study. Chinese Journal of Aeronautics, 35(2), 346-360.

[2] Drouot, A., Zhao, R., Irving, L., Sanderson, D., & Ratchev, S. (2018). Measurement assisted assembly for high accuracy aerospace manufacturing. IFAC-Papers On Line, 51(11), 393-398.

[3] Feng, Y. M., Dong, X. C., & Jin, T. (2019). Robot precision compensation method based on pso-elm. Computer Application Research (10).

[4] French, R., Benakis, M., & Marin-Reyes, H. (2017). Intelligent sensing for robotic re-manufacturing in aerospace—An industry 4.0 design based prototype. In 2017 IEEE International Symposium on Robotics and Intelligent Sensors. 272-277.

[5] Gao, L.F., Ge, Y.J., Wang, G.T., Zhu, Y.L., & Song, N. (2001). Study on signal processing system of six-dimension force sensor for space robot. Instrumentation Technology and Sensors (7), 3.

[6] Hong, P., Tian, W., Mei, D.Q., & Zeng, Y.F. (2015). Spatially meshing robot variable parameter accuracy compensation technology. Robotics, 37(3), 9.

[7] He, M. H. (2013). Research on online detection technology of robot automatic drilling and riveting based on multi-sensor integration.(Master's Thesis, Nanjing University of Aeronautics and Astronautics).

[8] Kong, L. B., & Yu, Y. (2022). Precision measurement and compensation of kinematic errors for industrial robots using artifact and machine learning. Advances in Manufacturing, 10(3), 397-410.

[9] Kumar, J. A., & Srinivas, G. (2019). Recent trends in Robots Smart Material and its application in Aeronautical and Aerospace Industries. In Journal of Physics: Conference Series (Vol. 1172, No. 1, p. 012035). IOP Publishing.

[10] Jiang, S. X. (2016). Research on calibration method of camera system oriented to pose estimation. (Doctoral dissertation, Huazhong University of Science and Technology).

[11] Jiang, Y., Huang, X., & Li, S. (2016). An on-line compensation method of a metrology-integrated robot system for high-precision assembly. Industrial Robot: An International Journal, 43(6), 647-656.

[12] Ju J.G., Zhang, N.N., Ren, Y.J., Yin, S.B., Guo, Y., & Guo, S.Y. (2018). On-line temperature compensation of industrial robot based on binocular stereo vision. Optics and Precision Engineering, 26(9), 11.

[13] Li, X. Q. (2012). Research on design and error compensation of a six-axis CNC aircraft assembly drilling and milling machine. (Doctoral dissertation, Nanjing University of Aeronautics and Astronautics).

[14] Lu, J., Sun, S. L., & Song, Y.Q. (2020). Visual positioning guidance system for automated precision assembly. Combined Machine Tools and Automated Processing Technology (2), 4.

[15] Liu, S. L., Tian, W., He, X.X., Tan, H., Liao, W.H, & Zhang, L. (2018). Robot precision compensation technology based on mechanical joint feedback. Aeronautical Manufacturing Technology, 61(4), 6.

[16] Li, D.K, Ye, S.H, Ren, Y.J., & Wang, Y. (2007). Research on calibration technology of robot positioning accuracy. Journal of Metrology, 28(3), 4.

[17] Liao, W.H, Tian, W., Li, B., Li, P.C., Zhang, W.& Li, Y.F. (2022). Robot precision compensation technology and application progress. Journal of Aviation (05),9-30+2.

[18] Li X. H. (2023). Development trend of manufacturing industry and upgrading direction of China's manufacturing industry. Frontiers in Academia (5), 51-58.

[19] Liu, X.P, Liu, B., Ma, Z.C, & Gao, L. (2017). Research and design of remote control assembly system based on machine vision. Automation Instrumentation, 38(11), 4.

[20] López, M. R., Sergiyenko, O., & Tyrsa, V. (2008). Machine vision: approaches and limitations. Computer vision, 395-428.

[21] Ma, L., Bristow, D. A., & Landers, R. G. (2018). Modeling and Compensation of Industrial Robot Kinematic Errors using a SmartTRACK Sensor. In Proceedings of the International Symposium on Flexible Automation 2018 International Symposium on Flexible Automation. 209-216.

[22] Nguyen, V. L., Kuo, C. H., & Lin, P. T. (2022). Compliance error compensation of a robot end-effector with joint stiffness uncertainties for milling: an analytical model. Mechanism and Machine Theory, 170, 104717.

[23] Shi, X.J, Zhang, F.M, Qu, X.H, Liu, B.L, & Wang, J. L. (2017). Pose measurement and Online error compensation of KUKA industrial robot. Journal of Mechanical Engineering, 53(8), 7.

[24] Shen, W.W, Jiang, X.Y, Zhang, B., & Guo, X.N. (2023). Accurate localization method of robot grasping visual sensing target. Journal of Sensing Technology, 36(5), 763-768.

[25] Schneider, U., Drust, M., Ansaloni, M., Lehmann, C., Pellicciari, M., Leali, F., ... & Verl, A. (2016). Improving robotic machining accuracy through experimental error investigation and modular compensation. The International Journal of Advanced Manufacturing Technology,85, 3-15.

[26] Sun, J.P, Tang, Z.P., Tang, Z,Y., & Chen, Z.X. (2019). A robot precision compensation method based on approximation weighted average interpolation. Chinese Journal of Scientific Instrument (11), 10.

[27] Wang, H.X, Wu, Q. F., Wu, X. B., & Zhang, Q.Y . (2022). Error compensation method for robot positioning accuracy. Mechanical and Electrical Engineering Technology (005), 051.

[28] Wang, Z., Zhang, R., & Keogh, P. (2020). Real-time laser tracker compensation of robotic drilling and machining. Journal of Manufacturing and Materials Processing, 4(3), 79.

[29] Wang, W., Tian, W., Liao, W., & Li, B. (2021). Pose accuracy compensation of mobile industry robot with binocular vision measurement and deep belief network. Optik, 238, 166716.

[30] Wang, T., Luo, Y, Wang, X.D, & Li, Y.W. (2020). Error analysis and compensation in precision assembly of wafer components. Aeronautical Manufacturing Technology, 63(7), 7.

[31] Yin, S.B. (2015). Research on classification compensation of positioning error and accuracy maintenance of industrial robots. (Doctoral dissertation, Tianjin University).

[32] Yuan, P., Chen, D., Wang, T., Cao, S., Cai, Y., & Xue, L. (2018). A compensation method based on extreme learning machine to enhance absolute position accuracy for aviation drilling robot. Advances in Mechanical Engineering, 10(3).

[33] Yang, S.R., Yin, S.B., Ren, Y.J., Zhu, J.G, & Ye, S.H. (2014). Improvement of calibration method of robot flexible vision measurement system. Optics and Precision Engineering, 22(12), 8.

[34] Zhou, W. (2012). Precision Compensation method and experimental research of industrial robot in Aircraft Automatic Assembly. (Doctoral dissertation, Nanjing University of Aeronautics and Astronautics).

[35] Zheng, F.Y. (2019). Robot precision compensation technology and application based on secondary feedback. (Doctoral dissertation, Nanjing University of Aeronautics and Astronautics).

[36] Zhu, W., Mei, B., Yan, G., & Ke, Y. (2014). Measurement error analysis and accuracy enhancement of 2D vision system for robotic drilling. Robotics and Computer-Integrated Manufacturing, 30(2), 160-171.

[37] Zhou, W., Liao, W.H, Tian, W., Li, D.M., & Liu, Y. (2012). Research on robot spatial mesh accuracy compensation for aircraft automated assembly. China Mechanical Engineering, 23(19), 6.

[38] Zhang, B.B. (2019). Mobile robot trajectory tracking control. Xidian University.