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Analysis of the Application of AI Visual Inspection Technology in Precision Mechanical Manufacturing Automation

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Abstract: In recent years, driven by the Industry 5.0 wave, precision mechanical manufacturing is accelerating its evolution toward ultra-precision, intelligence, and unmanned operation, posing unprecedented, stringent requirements for precision control, efficiency improvement, and cost optimization in the manufacturing process. As a core carrier of in-depth integration of artificial intelligence and industrial automation, AI visual inspection technology, with its advantages of non-contact inspection, real-time response, and adaptive learning, has gradually replaced traditional manual inspection and conventional machine visual inspection. It has become a key technical support for addressing pain points such as micro-defect identification, adaptation to complex working conditions, and full-process quality control in precision mechanical manufacturing. In this regard, this paper first analyzes the application scenarios of AI visual inspection technology in precision mechanical manufacturing automation, and then expounds the development trends of its applications in this field, to provide a reference for relevant researchers.

Keywords: AI visual inspection technology; Precision mechanical manufacturing; Automation; Application

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1. Application scenarios of AI visual inspection technology in precision mechanical manufacturing automation

1.1. Dynamic adaptive inspection in precision machining process

In precision mechanical machining, tool wear, workpiece deformation, deviations in cutting parameters, and other factors can reduce the dimensional accuracy of parts and components and cause surface defects. Most traditional inspection methods rely on offline inspection after machining is complete, which cannot detect abnormalities in the machining process in a timely manner, can easily lead to batch waste, and increase manufacturing costs. The application of AI visual inspection technology realizes dynamic adaptive inspection in the machining process, breaks through the traditional closed loop of “machining–inspection–rework”, and establishes an automatic closed-loop mode of real-time inspection–timely adjustment–precise machining [1].

Compared with traditional offline inspection, the new AI visual inspection technology can be embedded in the core parts of processing equipment, such as the spindle and turret. It employs high-frame-rate industrial cameras and adaptive light sources to capture dynamic images during tool cutting, and then uses deep learning algorithms to instantly identify and quantitatively evaluate tool wear, workpiece surface roughness, dimensional deviation, and other indicators. Meanwhile, this technology possesses strong adaptive learning capability. It can automatically adjust inspection parameters and identification models based on the characteristics of different processing materials and technologies, without manual recalibration, making it suitable for multi-type, small-batch precision machining. Taking the precision grinding of aero-engine blades as an example, AI visual inspection technology can monitor micro-scratches, edge chipping, and other defects on the blade surface in real time, as well as the wear of grinding tools. Once abnormalities are detected, feedback signals will be sent to the numerical control system to automatically adjust parameters such as grinding speed and feed rate, prevent defects from spreading further, and ensure that blade machining accuracy meets micron-level requirements [2].

1.2. Intelligent positioning and error compensation in precision assembly links

Precision mechanical assembly is a key link determining product performance and reliability. In fields such as aerospace and medical devices, where parts and components require high assembly accuracy, even tiny assembly errors can lead to product failure. In the past, assembly positioning was mostly done manually based on experience, resulting in low efficiency and a high risk of assembly errors caused by human operator mistakes, which did not meet the requirements of automated assembly. The application of AI visual inspection technology transforms positioning, inspection, and correction in precision assembly from manual operation to intelligent positioning, real-time detection, and dynamic adjustment. The assembly process has changed from manual assistance to full automation, greatly improving assembly efficiency and accuracy.

By adopting multi-camera collaborative acquisition and 3D visual modeling technologies, AI visual inspection technology can quickly obtain the three-dimensional spatial coordinates and surface features of parts to be assembled. It uses deep learning algorithms to accurately compare with preset assembly standard models, automatically identify assembly abnormalities such as part position and angle deviations, calculate compensation in real time, and control assembly robots to achieve accurate positioning and assembly. Different from traditional 2D visual positioning, AI visual inspection technology based on the integration of structured light and laser triangulation can accurately acquire the 3D contour information of parts, effectively solving the problems of missing Z-axis direction information and susceptibility to light interference in 2D visual inspection, and meeting the assembly requirements of parts with complex structures. In the assembly of micro precision gearboxes, the adopted AI visual inspection system can simultaneously scan the positions of gears, bearings, shafts and other components, automatically detect the meshing clearance between gears and the assembly correctness of bearings, and then adjust the moving mode of assembly robots according to the above information to ensure the gear meshing accuracy meets design standards, with the assembly efficiency increased by more than 5 times [3].

1.3. Non-contact precision inspection under extreme working conditions

The manufacturing and inspection processes for precision mechanical products must be carried out under extreme working conditions, such as high temperatures, high pressures, intense radiation, and high vacuum.

Traditional contact inspection methods easily damage part surfaces, and inspection equipment can hardly operate reliably under extreme working conditions, thereby compromising inspection accuracy. Thanks to the characteristics of non-contact inspection, AI visual inspection technology employs high-temperature- and radiation-resistant industrial cameras, along with adaptive imaging technology, to inspect precision parts under extreme working conditions, thereby breaking the application boundaries of traditional inspection technology [4].

For example, in the pouring process of precision castings, high-temperature resistant industrial cameras and infrared imaging technology can penetrate high-temperature smoke, observe the casting pouring situation in real time, accurately locate defects such as air holes, cracks, and shrinkage cavities on the casting surface, and monitor the dimensional changes of castings, providing data support for timely adjustment of pouring technology. Compared with traditional inspection methods, this non-contact inspection method neither damages inspection equipment due to high temperatures nor enables real-time monitoring of the pouring process, thereby preventing casting defects. During inspections of precision parts in nuclear reactors, radiation-resistant cameras, combined with remote control, are used to examine surface defects and the parts' dimensional accuracy, thereby improving inspection efficiency and accuracy while ensuring operator safety [5].

1.4. Predictive inspection and operation & maintenance of full life cycle

Traditional inspection in precision mechanical manufacturing primarily focuses on the machining and assembly stages, with insufficient attention to condition monitoring and early fault warning during product service. Products are prone to failure due to hidden defects in the service process, which increase operation and maintenance costs and pose safety risks. AI visual inspection technology can enable predictive inspection and operation & maintenance across the full life cycle of precision mechanical products, break the previous thinking that emphasizes manufacturing while ignoring operation & maintenance, and establish an automatic control system that integrates manufacturing, inspection, and operation & maintenance. During product service, the AI visual inspection system can be embedded in key equipment components. It uses real-time acquired image data of the product operation process, combined with deep learning algorithms and big data analysis methods, to detect hidden flaws on the product surface, monitor product operation parameter indicators, establish a product service condition prediction model, so as to send fault early warning signals in advance and provide strong data support for operation and maintenance decision-making. For example, miniature industrial cameras are installed inside aero-engines during service to monitor wear, cracks, and other conditions on the blade surface in real time. Combined with parameters such as vibration and temperature during blade operation, the remaining service life of blades can be predicted, enabling maintenance and replacement in advance and preventing safety accidents caused by engine failures [6].

1.5. Composite inspection application of multimodal fusion

At present, the structure of precision mechanical products is becoming increasingly complex, and single-modal visual inspection can no longer meet the requirements of multi-type and multi-dimensional inspection. In recent years, multimodal fused AI visual inspection technology has gradually become popular. By integrating multiple inspection modalities such as visible light, infrared, X-rays, and lasers, it enables multi-angle, all-round inspection of precision mechanical parts, breaks the constraints of single-modal inspection, and improves the comprehensiveness and accuracy of inspection. Meanwhile, multimodal-fused AI visual inspection technology can meet the inspection requirements for parts with complex materials. For example, single-modal inspection has difficulty identifying surface and internal defects in precision parts made of special materials such as carbon fiber composites and ceramics, whereas multimodal fused inspection can effectively overcome this difficulty and achieve accurate inspection. When inspecting precision parts made of carbon fiber composites, multimodal AI visual inspection technology can detect internal delamination, pores, and other defects. The composite inspection application of multimodal fusion can broaden the scope of AI visual inspection technology, improve the comprehensiveness and accuracy of inspection, and provide a new solution for quality control of complex precision mechanical products [7].

2. Development trends of AI visual inspection technology in precision mechanical manufacturing automation

2.1. Continuous breakthrough of ultra-precision inspection technology

As precision mechanical manufacturing moves toward nanometer-level accuracy, AI visual inspection technology will continue to make breakthroughs in ultra-precision inspection, continuously improving accuracy and resolution. On the one hand, high-resolution imaging technology will continue to advance, and new nanometer-level industrial cameras and laser imaging equipment will gradually become more widely adopted, enabling accurate detection of nanometer-level micro-defects and dimensional deviations. On the other hand, deep learning algorithms will be continuously optimized, and new algorithms based on the fusion of Transformer and CNN will be gradually applied to achieve accurate feature extraction and the identification of complex-structured parts, thereby improving the model’s generalization ability and detection accuracy [8].

At the same time, integrating quantum imaging, terahertz imaging, and other technologies with AI-based visual inspection can overcome the limitations of traditional imaging, accurately detect internal defects in precision mechanical parts, and enable comprehensive inspection without damaging the parts, thereby providing technical support for ultra-precision mechanical manufacturing. In addition, AI visual inspection technology can penetrate the product surface to accurately detect internal micro-cracks, inclusions, and other defects, achieving nanometer-level inspection accuracy. It is widely used in high-end precision mechanical manufacturing fields such as aerospace and microelectronics.

2.2. In-depth and collaborative development of technology integration

AI visual inspection technology will be deeply integrated with emerging technologies such as edge computing, 5G, digital twin, and blockchain, thereby continuously improving the coordination and compatibility of these technologies and establishing a full-process, intelligent, and integrated automatic management and control system for precision mechanical manufacturing. First, it is deeply integrated with edge computing to enable real-time processing of inspection data, reduce data transmission delays, improve real-time inspection performance, and closely match the demands of high-speed automated production. Deep integration with 5G technology enables high-speed data transmission and sharing among multiple devices and systems, breaks down data silos, and achieves full-process collaborative management and control [9].

Second, the deep integration of AI visual inspection technology and digital twin technology will form a digital twin model of precision mechanical products, realizing real-time synchronization of inspection data and product digital models, simulating the manufacturing and service process of products, so as to improve machining, assembly, and operation & maintenance strategies and achieve precise manufacturing and precise operation & maintenance. Meanwhile, through in-depth integration with blockchain technology, inspection data can be traced throughout the process and cannot be tampered with at will, thereby improving its authenticity and reliability and effectively controlling product quality. In addition, AI visual inspection technology is closely integrated with robots, enabling seamless collaboration between inspection and operations. Installing visual inspection devices on robots can automatically perform operations such as parts inspection, sorting, and rework, enabling full-process automation of precision mechanical manufacturing, reducing errors caused by manual intervention, improving the stability and efficiency of complex operational links, and further releasing the production capacity potential of precision manufacturing.

2.3. Mult scenario adaptive and intelligent upgrade

AI visual inspection systems will have a wider adaptive range, automatically adapting to various processing methods, product varieties, and working environments. They can automatically adjust inspection parameters and actively adapt to models without human intervention, realizing "one-click inspection". Taking the iteration of precision mechanical products as an example, the AI visual inspection system can automatically identify the characteristics of new products, quickly adjust inspection models and parameters without manual recalibration and training, realize accurate inspection of new products, and quickly respond to the customized production demand of multi-variety and small-batch production in the precision manufacturing field.

AI visual inspection technology is gradually developing toward higher intelligence. By adopting reinforcement learning, deep learning, and other technologies, the inspection model can self-optimize and upgrade, adjust its identification strategies in response to changes in inspection data, and continuously improve inspection accuracy and speed. In addition, AI visual inspection systems will have stronger independent decision-making capabilities and can automatically determine rework and parameter adjustments based on inspection results, thereby integrating inspection and disposal, reducing human intervention, and promoting the continuous transformation of precision mechanical manufacturing toward automation [10].

3. Conclusion

In a word, with the outstanding advantages of non-contact, high precision, and intelligence, AI visual inspection technology has been deeply integrated into the whole process of machining, assembly, operation, and maintenance of precision mechanical manufacturing automation. It has shown significant technical value in multiple typical application scenarios, effectively addressing the pain points of traditional inspection technology, such as insufficient precision, poor timeliness, and limited applicability, and providing core technical support for quality control and the automation upgrade of precision mechanical manufacturing. In the future, with the continuous breakthrough of ultra-precision imaging technology and deep learning algorithms as well as the in-depth integration with various emerging technologies, AI visual inspection technology will further upgrade toward adaptiveness and intelligence, continuously expand its application boundary in the field of high-end precision manufacturing, provide stronger power for the development of precision mechanical manufacturing automation, promote the high-end equipment manufacturing industry to develop toward higher precision and higher efficiency, and better support the high-quality development of China's high-end manufacturing industry.

Disclosure statement

The author declares no conflict of interest.

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