

Application Analysis of Machine Vision in Quality Inspection of Intelligent Factory Assembly Lines

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Keywords: Machine vision; Intelligent factory; Assembly line; Quality inspection; Automated inspection

Abstract: With the rapid development of intelligent manufacturing and smart factories, assembly line production processes have placed higher demands on the timeliness, accuracy, and stability of quality inspection. Traditional manual inspection and contact-based detection methods are increasingly unable to meet the requirements of modern industrial quality control under conditions of high production speed, complex operating environments, and multi-variety manufacturing. Owing to its non-contact nature, high efficiency, and ease of system integration, machine vision technology has gradually become an important technical approach for quality inspection on intelligent factory assembly lines. This paper focuses on the application of machine vision in assembly line quality inspection within intelligent factories. First, the typical requirements and key characteristics of assembly line quality inspection are analyzed, followed by a systematic discussion of the basic principles and key technologies of machine vision systems. On this basis, a machine vision system architecture oriented toward assembly line quality inspection is constructed, and the inspection workflow and implementation methods are examined in detail. Through a practical application case, the performance of the machine vision inspection system is evaluated in terms of detection accuracy, inspection efficiency, and operational stability. The results indicate that machine vision technology can effectively enhance the level of automation and consistency in assembly line quality inspection, providing reliable technical support for quality management in intelligent factories.

1. Introduction

Amid a new wave of industrial technological transformation, intelligent manufacturing has emerged as a key direction for the upgrading of the manufacturing industry. As the core carrier of intelligent manufacturing, smart factories depend heavily on the automation, informatization, and intelligence of their production processes, which directly influence production efficiency and product quality. As a critical link between component processing and final product manufacturing, the assembly line plays a decisive role in ensuring product consistency and production stability. With increasing product complexity and accelerating production rhythms, assembly-related quality issues have become more diverse and concealed, revealing the limitations of traditional quality inspection methods based on manual experience or contact-based equipment, including low

efficiency, strong subjectivity, and limited adaptability. In this context, non-contact automated inspection technologies have attracted growing attention. Among them, machine vision technology has shown strong potential in industrial quality inspection due to its high inspection speed, good repeatability, and ease of integration with automated systems. By performing real-time image acquisition and analysis at key assembly processes, machine vision systems can rapidly detect dimensional deviations, assembly defects, and surface anomalies, enabling online monitoring and timely quality feedback. This approach reduces manual intervention, improves inspection consistency, and provides valuable data support for process optimization and quality traceability. In recent years, advances in image processing algorithms and artificial intelligence have further expanded the application of machine vision in assembly line quality inspection. However, challenges remain in constructing stable and reliable systems under complex lighting conditions, mixed production of multiple product types, and high-speed operation. Therefore, a systematic analysis of application modes and system implementation strategies is necessary. Based on these considerations, this study investigates the application of machine vision in intelligent factory assembly line quality inspection, focusing on inspection requirements, key visual technologies, system design, and application performance, and provides references for the optimization of quality inspection systems in intelligent factories.

2. Quality Inspection of Intelligent Factory Assembly Lines and Fundamentals of Machine Vision Technology

2.1 Analysis of Quality Inspection Requirements for Intelligent Factory Assembly Lines

In intelligent factory production systems, assembly lines are responsible for integrating multiple components into final products, and their quality performance directly affects product reliability and manufacturing capability. Compared with traditional production modes, intelligent factory assembly lines are characterized by high production speed, continuous processes, and a high level of automation. This requires quality inspection systems to provide real-time monitoring without disrupting production efficiency. Failure to promptly detect issues such as dimensional deviations, incorrect assembly, or missing components may lead to large-scale quality risks and cascading effects on subsequent processes, placing strict demands on inspection timeliness and accuracy[1]. As product complexity increases and market demand shifts toward customization, assembly lines increasingly operate in multi-variety, small-batch, and mixed-line production modes. Differences in product structures, assembly processes, and quality standards require inspection systems to be flexible and adaptable. Inspection methods must rapidly accommodate changes in product specifications while maintaining stable performance, which is difficult to achieve with traditional approaches relying heavily on manual experience. Furthermore, intelligent factories emphasize digitalized and data-driven production. Quality inspection systems are expected to function not only as pass–fail decision tools but also as data sources for process control. This requires strong data acquisition, analysis, and integration capabilities to support real-time feedback and quality trend monitoring. In complex industrial environments, challenges such as lighting variations, equipment vibration, and limited installation space further increase demands on system robustness and stability. Overall, these requirements provide a practical foundation for adopting machine vision–based quality inspection in intelligent factory assembly lines[2].

2.2 Principles and Development Status of Machine Vision Technology

Machine vision technology is an intelligent perception approach based on computer vision and digital image processing, enabling the automatic acquisition and interpretation of object information

through optical imaging and algorithmic analysis. In industrial applications, machine vision systems typically include imaging units, image acquisition modules, processing and analysis units, and output and control interfaces[3]. Under controlled lighting conditions, industrial cameras capture images of inspected objects, from which key features are extracted and evaluated using predefined rules or trained models. This non-contact, highly repeatable, and fast-response process satisfies the requirements of real-time and stable online inspection on assembly lines. From a technical perspective, effective image representation and analysis are fundamental to machine vision inspection. Proper lighting and imaging design enhance contrast between targets and backgrounds, while preprocessing techniques suppress noise, correct distortions, and highlight critical regions. Traditional machine vision methods rely on manually designed features and rule-based analysis of edges, shapes, textures, or geometric relationships. These methods are computationally efficient and easy to interpret but exhibit limited adaptability in complex scenarios with diverse defect types. With advances in computing power and artificial intelligence, deep learning-based machine vision methods have gained increasing attention. By training deep neural networks on large datasets, systems can automatically learn discriminative features, achieving higher accuracy and robustness under complex backgrounds and variable conditions. Currently, machine vision is widely applied in electronics manufacturing, automotive assembly, and precision machining, and is increasingly integrated with automation and production management systems. Its development trend emphasizes intelligent algorithms, deeper system integration, and expanding application scenarios in intelligent factories[4].

3. Key Visual Technologies for Assembly Line Quality Inspection

3.1 Image Acquisition and Preprocessing Techniques in Assembly Line Quality Inspection

In assembly line quality inspection, image acquisition is the foundational step for obtaining reliable information in machine vision systems, as image quality directly affects the stability and accuracy of subsequent inspection algorithms. Since assembly lines operate continuously and products pass inspection stations at fixed speeds, the acquisition system must satisfy real-time requirements while maintaining clear and consistent imaging. As illustrated in Figure 1, a typical assembly line inspection system comprises industrial cameras, lenses, light sources, and mounting structures. By installing imaging devices above or beside key assembly stations and selecting appropriate viewing angles, stable online capture of assembly states can be achieved while minimizing background interference.

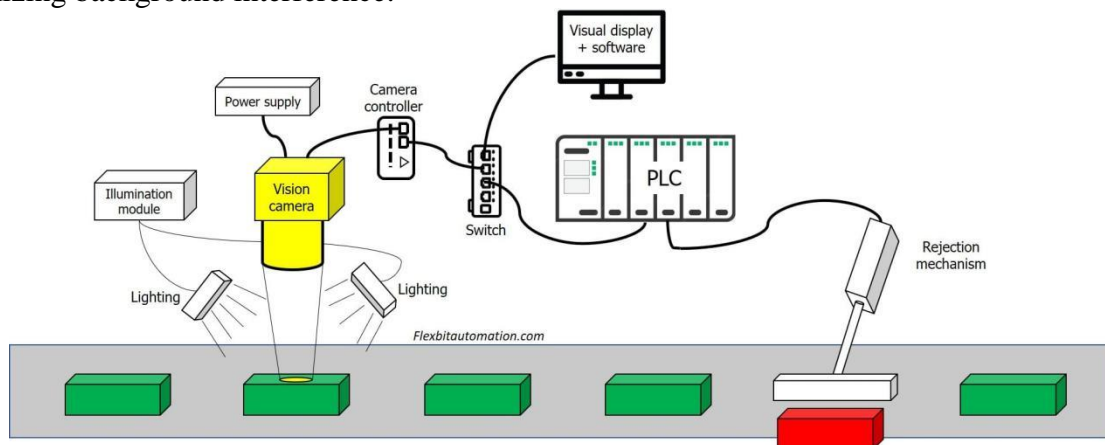


Figure 1. Image acquisition system in assembly line quality inspection

Lighting conditions are a critical factor influencing image quality in industrial environments.

Assembly lines often experience ambient light variations, surface reflections, and complex component textures, which may degrade image clarity if not properly controlled. To address this issue, machine vision systems commonly employ dedicated industrial light sources to provide directional and stable illumination. By adjusting light source type, angle, and intensity distribution, the contrast between inspection targets and backgrounds can be significantly enhanced, improving the visibility of structural and edge features. Following image acquisition, preprocessing techniques such as noise reduction, grayscale transformation, contrast enhancement, and geometric correction are applied to further improve image quality. These operations suppress environmental disturbances and highlight regions relevant to quality evaluation, making defects more distinguishable[5]. Overall, well-designed image acquisition and preprocessing strategies provide stable, high-quality inputs and form a solid technical foundation for high-precision assembly line quality inspection.

3.2 Defect Recognition and Quality Decision Methods

Building on high-quality image acquisition and preprocessing, defect recognition and quality decision-making form the core functions of machine vision systems for assembly line quality control. This stage aims to extract assembly-related quality information from processed images and determine product conformity based on predefined standards. Typical inspection tasks include verifying assembly positions, detecting missing or incorrectly installed components, and identifying visible surface defects, all of which require high recognition accuracy and rapid response. Traditional machine vision defect recognition methods are primarily based on manually designed features and rule-based logic. By analyzing edges, contours, geometric dimensions, or grayscale distributions, these approaches can effectively evaluate assembly states in scenarios with clear structural features and relatively fixed defect types. Their advantages include low computational complexity, good real-time performance, and strong interpretability[6]. However, as assembly structures become more complex and defect patterns more diverse, such methods often require frequent parameter tuning, limiting system adaptability and long-term stability. With advances in artificial intelligence, deep learning-based defect recognition methods have been increasingly applied in assembly line inspection. By training deep neural networks on large datasets, these methods can automatically learn discriminative features, offering greater robustness under complex backgrounds, variable lighting conditions, and diverse defect types. They are particularly effective for surface defect detection and multi-class assembly state classification. Nevertheless, their higher demands on data availability, computational resources, and model maintenance must be carefully considered in practical deployment. In the quality decision stage, recognition results are compared with predefined standards to generate clear pass or fail judgments, which are fed back to control systems for automated handling. Appropriate selection and integration of recognition and decision methods are therefore essential for reliable and practical assembly line inspection[7].

4. Design and Implementation of a Machine Vision-Based Assembly Line Quality Inspection System

4.1 Overall Architecture Design of the Machine Vision Quality Inspection System

To satisfy the comprehensive requirements of intelligent factory assembly lines with respect to real-time performance, operational stability, and system coordination, machine vision quality inspection systems generally adopt a layered and modular architecture. As illustrated in Figure 2, the system can be divided into three main layers: the image acquisition layer, the vision processing layer, and the control and information interaction layer. Standardized interfaces are used to enable coordinated transmission of data and control signals among these layers, forming an integrated technical framework for assembly line quality inspection. This architectural approach enhances

system scalability and engineering feasibility, facilitating deployment and adjustment across different assembly stations and production scenarios[8].

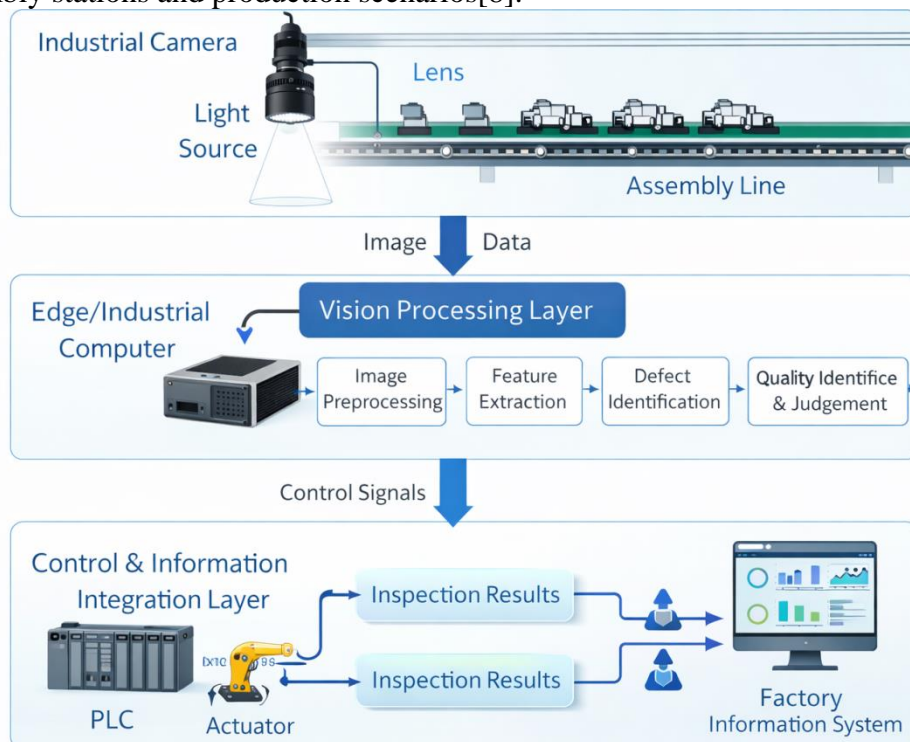


Figure 2. Architecture Diagram of the quality inspection system for the intelligent factory

The image acquisition layer is responsible for converting physical assembly states into digital image information. Industrial cameras, lenses, and dedicated lighting units are deployed at key inspection stations along the assembly line to perform online imaging of assembled products. Through appropriate configuration of imaging angles and illumination modes, stable and high-quality image data can be obtained without disrupting the assembly rhythm. The performance of this layer directly affects the upper performance limit of the entire inspection system and provides reliable input for subsequent visual analysis[9]. The vision processing layer constitutes the core functional component of the system. It performs image preprocessing, feature extraction, defect recognition, and quality judgment in real time based on predefined rules or trained models. As shown in Figure 2, this layer is typically implemented on industrial computers or edge computing devices to ensure high processing efficiency and rapid system response. A modular design allows inspection algorithms and decision strategies to be flexibly configured, enabling adaptation to different product types and varying quality inspection requirements. The control and information interaction layer integrates visual inspection results with the assembly line control system and production management system. Inspection outcomes can be fed back in real time to programmable logic controllers or actuators to trigger actions such as defective product rejection or alarm signaling. Meanwhile, quality data are transmitted to higher-level information systems to support quality traceability, statistical analysis, and process optimization. Through this multi-layer collaborative architecture, the machine vision quality inspection system not only realizes online quality judgment but also serves as a key information node for quality management and process control in intelligent factories. Overall, the system architecture emphasizes a closed-loop process from perception and analysis to decision execution. Through well-structured layering and standardized interface design, it provides a solid foundation for stable operation and future functional expansion of assembly line quality inspection systems[10].

4.2 Assembly Line Quality Inspection Workflow and System Implementation

Based on the overall architecture of the machine vision quality inspection system, a well-designed inspection workflow is critical to ensuring stable operation and effective inspection performance. The workflow is organized around the assembly line production rhythm and enables continuous execution of image acquisition, visual analysis, and quality judgment through coordinated control with production equipment. When a product enters the inspection station, image acquisition is triggered by position sensors or assembly line control signals. Under controlled lighting conditions, industrial cameras capture real-time images of key assembly areas, ensuring that each product is associated with complete and clear inspection data. Captured images are transmitted in real time to the vision processing unit, where image preprocessing, feature extraction, and defect recognition are performed sequentially according to predefined procedures[11]. Preprocessing primarily aims to suppress environmental noise and lighting fluctuations, providing stable input for subsequent analysis. Appropriate recognition algorithms are then applied based on specific inspection tasks to analyze assembly states and generate recognition results. These processes are typically executed on industrial computers or edge computing devices to guarantee real-time responsiveness under high-speed production conditions. During the quality judgment stage, recognition results are compared with predefined quality standards to produce clear pass or fail decisions. The decisions are fed back to the assembly line control system to trigger automatic marking, sorting, or alarm actions for nonconforming products. Meanwhile, inspection results and image data are recorded and uploaded to production management systems to support quality statistics and traceability. Through modular software design and standardized interfaces, the system achieves high reliability, maintainability, and flexible adaptation to changing assembly processes, thereby strengthening quality control capabilities in intelligent factory assembly lines[12].

5. Application Case Study and Performance Evaluation

5.1 Application of Machine Vision–Based Quality Inspection on an Assembly Line

To evaluate the practical effectiveness of the proposed machine vision quality inspection system, an automotive electronics assembly line was selected as an application case. The line is mainly used for assembling in-vehicle control modules, which are characterized by compact structures, high precision requirements, and fast production rhythms. These features impose strict demands on the real-time performance and consistency of quality inspection[13]. In actual production, common defects include missing components, incorrect installation of key electronic parts, and assembly position deviations, which cannot be effectively controlled through traditional manual sampling inspection. To address these challenges, a machine vision quality inspection system was deployed at key assembly stations to enable online inspection of critical processes. Industrial cameras and dedicated lighting units were installed above the stations to capture real-time images of products passing through the inspection area. The system was integrated with the assembly line control system without modifying the original production process, allowing image acquisition to be automatically triggered when products enter the inspection zone, thereby ensuring full inspection coverage. During operation, the system performs image preprocessing and feature analysis to evaluate key assembly positions based on predefined rules and models. Detected abnormalities trigger immediate nonconformance signals and corresponding sorting or marking actions, while inspection data are uploaded for quality analysis and traceability. Stable performance under high-speed conditions confirms the engineering feasibility of machine vision–based inspection in intelligent factory assembly lines[14].

5.2 Quality Inspection Performance and Effectiveness Analysis

Based on the application case described above, the performance of the machine vision quality inspection system was comprehensively evaluated to verify its feasibility and practical value in real production environments. In terms of detection accuracy, the system can reliably identify common assembly defects, including missing components, incorrect installation, and positional deviations, through automated image recognition and decision-making. Compared with manual visual inspection, machine vision provides higher consistency and is free from subjective influences, effectively reducing misjudgments and missed detections caused by operator fatigue or experience differences during long-term operation. With respect to inspection efficiency, the machine vision system enables online inspection of every product without disrupting the assembly line rhythm. As image acquisition and visual processing are synchronized with assembly operations, inspection is completed within a single production cycle. This full-inspection mode significantly increases inspection coverage compared with manual sampling and helps prevent the accumulation of quality risks while avoiding production bottlenecks. System stability is another critical indicator of engineering applicability. In practice, the system maintains stable and continuous operation under complex industrial conditions and shows adaptability to lighting variations and assembly rhythm fluctuations. Through appropriate lighting design and preprocessing strategies, inspection results remain consistent over extended operation periods. From a labor substitution perspective, the system reduces reliance on manual inspection by shifting human roles toward system monitoring and exception handling, thereby improving labor efficiency and enhancing the controllability and traceability of assembly line quality management[15].

6. Problem Analysis and Development Trends

Although machine vision technology has demonstrated strong potential in assembly line quality inspection, several challenges remain in practical engineering deployment that currently limit its broader application in intelligent factories. Assembly line environments are inherently complex and dynamic, where variations in lighting conditions, equipment vibration, and component surface reflectivity can significantly degrade image quality. Even with dedicated illumination and preprocessing techniques, image instability may persist in certain scenarios, particularly in high-speed stations with constrained installation space, thereby affecting the reliability and accuracy of defect recognition. At the same time, the growing adoption of multi-variety, small-batch, and mixed-line production increases the structural and visual diversity of inspection targets. For traditional rule- and feature-based vision methods, frequent changes in product models or assembly processes often require extensive parameter tuning or workflow redesign, reducing system flexibility and increasing maintenance effort. Although deep learning-based approaches offer improved robustness, they also face challenges related to data availability, long model training cycles, and delayed updates, making rapid adaptation difficult in frequently changing production environments. In addition, deployment and operational costs remain a critical concern, as high-performance cameras, specialized lighting, and edge computing devices increase initial investment, while system commissioning, algorithm optimization, and maintenance demand skilled personnel. These cost factors are particularly significant for small- and medium-scale assembly lines or low-value-added products, where return on investment must be carefully evaluated. From a system integration perspective, effective application of machine vision requires deep integration with assembly line control systems and production management platforms; however, heterogeneous communication protocols and interface standards often increase integration complexity, potentially leading to data latency or information silos that reduce the practical value of inspection results in production decision-making. Looking ahead, the development of machine vision in intelligent

factories is moving toward higher intelligence and deeper integration with emerging technologies. Closer coupling with artificial intelligence methods such as deep learning, transfer learning, and adaptive learning will enhance the system's ability to recognize complex assembly scenarios and diverse defect types while improving generalization and environmental adaptability. At the same time, machine vision is becoming an essential node within industrial internet architectures, enabling cross-system data sharing for quality traceability, process optimization, and predictive maintenance. Advances in edge and cloud computing further support flexible deployment through "cloud-edge-end" collaborative architectures, combining real-time local processing with centralized model management and knowledge sharing. Overall, machine vision is evolving from a standalone inspection tool into a core component of intelligent manufacturing systems, playing an increasingly important role in quality control, production optimization, and intelligent decision support.

7. Conclusion

This study systematically examines the application of machine vision in quality inspection for intelligent factory assembly lines. Based on assembly line inspection requirements, machine vision principles and key visual technologies were integrated to analyze system architecture, inspection workflows, and practical application performance. A representative assembly line case demonstrates that machine vision effectively improves inspection automation and consistency, highlighting its value in intelligent factory quality control. The results show that machine vision-based systems enable real-time inspection and rapid feedback without disrupting production rhythm. Detection accuracy and inspection coverage are significantly enhanced, while subjective errors and labor intensity associated with manual inspection are reduced. The systems also exhibit good stability and engineering feasibility in complex industrial environments. Nevertheless, challenges remain, including limited adaptability to complex conditions, relatively high deployment and maintenance costs, and integration complexity with production management systems. Future developments combining artificial intelligence, industrial internet, and edge computing are expected to further enhance machine vision capabilities, extending its role from quality inspection to broader production optimization in intelligent manufacturing systems.

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