

# Practical Application of Low-Cost Visual Inspection Systems in Industrial Robot Integration

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**Abstract:** In the transformation of industrial automation to smart manufacturing, visual inspection systems as critical sensing technologies are hindered by their high costs and algorithmic complexity, impeding the intelligent upgrading of small and medium-sized enterprises. This study focuses on low-cost visual inspection systems, enhancing performance through the selection of domestic industrial cameras, optimization of OpenCV and lightweight deep learning model algorithms, and the use of a C++ parallel computing framework, thereby constructing a solution that balances accuracy and cost. Experiments demonstrate that the system achieves sub-millimeter-level positioning and highly reliable detection in scenarios such as assembly guidance and defect identification, significantly reducing hardware costs while maintaining millisecond-level response capabilities, providing a feasible path for the intelligent upgrading of small and medium-sized enterprises.

**Keywords:** Low-cost visual inspection system; Industrial robot integration; Defect identification; Intelligent manufacturing

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## 1. Introduction

Driven by Industry 4.0 and intelligent manufacturing strategies, industrial robots are evolving from single repetitive tasks to flexible and intelligent directions. The core challenge of their integrated applications lies in how to achieve human-machine collaboration and quality closed-loop control through efficient perception technology. As a key module for robots to perceive the external environment, the visual inspection system relies on high-precision industrial cameras and complex algorithm architectures in traditional solutions, leading to bottlenecks for small and medium-sized enterprises such as high equipment costs, long deployment cycles, and difficult maintenance. This study focuses on the technological breakthrough of low-cost visual inspection systems and the integration practice of industrial robots to address this pain point. It explores the construction of a solution that balances detection accuracy and economy through domestic hardware substitution, algorithm lightweight design, and system level optimization, providing theoretical support and technical path for the popularization of intelligent manufacturing.

## 2. Technical foundation of low-cost visual inspection system

The technical foundation of low-cost visual inspection systems covers three core dimensions: hardware selection, algorithm architecture, and system integration. On the hardware level, a combination of domestically produced industrial cameras and LED light sources is adopted, which significantly reduces hardware costs while meeting the detection needs of industrial scenes by reducing sensor resolution and optimizing optical path design. At the algorithmic level, a traditional image processing pipeline is built based on OpenCV, combined with lightweight deep learning models<sup>[1]</sup>. Through knowledge distillation and quantization compression techniques, the model parameters are reduced by more than 80%, achieving real-time inference of edge devices. At the system integration level, ROS is used as middleware to achieve asynchronous data exchange between the visual module and the industrial robot controller through topic/service communication mechanism. Multi thread scheduling strategy is utilized to balance the timing relationship between image acquisition, processing, and instruction issuance, ensuring the robustness and millisecond response capability of the system in complex industrial environments.

## 3. Application scenarios of visual inspection in industrial robot integration

### 3.1. Assembly process: High-precision guidance and positioning

In precision assembly scenarios, visual inspection systems need to address the challenges of compensating for workpiece pose deviations and coordinating multi degree of freedom control. Taking the assembly of automobile engine pistons as an example, traditional mechanical positioning has a failure rate of up to 5% due to machining errors of the workpiece. However, the visual guidance scheme collects real-time image data of the piston and cylinder bore through an industrial camera, combined with a point cloud registration algorithm based on RANSAC, which can complete the estimation of the 6-degree-of-freedom pose of the workpiece within 0.3 seconds<sup>[2]</sup>. The system adopts a binocular stereo vision architecture and effectively overcomes the interference of metal surface reflections through epipolar correction and disparity optimization algorithms, ensuring stable operation within a 300lx illumination fluctuation range. Furthermore, the vision system and industrial robot controller achieve millisecond level communication through the EtherCAT bus, issuing real-time pose compensation instructions to the robotic arm, increasing the assembly success rate to 99.7% and shortening the single piece assembly cycle to 8 seconds, resulting in a 40% increase in efficiency compared to traditional solutions.

### 3.2. Inspection process: Defect identification and quality control

Defect detection is the core application scenario of visual inspection systems, and its technical challenge lies in the recognition of small defects and classification of multiple types of defects in complex backgrounds. In PCB board defect detection, the system uses an 8K line scanning camera to capture images with a resolution of 20  $\mu\text{m}$ . Combined with the U-Net++ semantic segmentation model, it can identify defects such as 0.1 mm level circuit short circuits, open circuits, and pad oxidation. To address the problem of slow inference speed in traditional deep learning models, channel pruning and knowledge distillation techniques were used to compress the model parameters to 1.2 MB, and real-time detection at 15 fps was achieved on NVIDIA Jetson AGX Xavier edge devices. For the detection of foreign objects in food packaging, the system innovatively integrates X-ray transmission imaging and hyperspectral analysis technology, and uses support vector machine classifiers to identify materials such as glass, metal, plastic, etc. The detection accuracy reaches 98.6% at a particle size of 0.5 mm, reducing the missed detection rate by 72% compared to a single sensor solution. In addition, the system integrates a defect database and quality traceability module to achieve correlation analysis between production

batches and defect types, providing data support for process optimization.

### **3.3. Handling and sorting process: Dynamic tracking and path planning**

In high-speed logistics sorting scenarios, visual inspection systems need to solve the collaborative control problem of motion target tracking and dynamic path planning <sup>[3]</sup>. Taking parcel sorting in e-commerce warehouses as an example, the system uses a combination of a global shutter camera and a strobe LED light source to capture clear images of moving parcels at a sampling rate of 1000fps. Combined with the KCF tracking algorithm, it achieves continuous target positioning and maintains a tracking success rate of over 95% even in cases of overlapping or obstructed parcels. In response to the dynamic programming requirements of the robotic arm grasping point, the system predicts the center of gravity position of the package through a deep learning model, and combines the A\* algorithm to generate collision free motion paths, improving sorting efficiency to 3600 pieces/hour, which is 60% more efficient than traditional fixed path schemes. Furthermore, the system integrates a hybrid control strategy of force control sensors and visual feedback, which adjusts the grasping force in real-time when grabbing fragile items, reducing the breakage rate from 3% to 0.2% and significantly improving the reliability of sorting operations.

### **3.4. Grinding and processing process: Surface quality monitoring**

In the scenario of metal surface polishing, the visual inspection system needs to achieve real-time monitoring of processing quality and closed-loop control of process parameters. Taking the polishing of aviation aluminum alloy components as an example, the system uses a multispectral camera to collect surface reflection spectra, extracts texture features through principal component analysis, and combines a random forest model to classify and identify defects such as scratches, ripples, and over grinding <sup>[4]</sup>. The detection accuracy reaches 97.3% under surface roughness changes of 0.02 mm. In response to the optimization requirements of polishing process parameters, the system establishes a BP neural network prediction model for surface quality, sand belt pressure, feed rate and other parameters. By adjusting the processing parameters in real time, the surface roughness Ra value is stabilized within 0.8  $\mu\text{m}$ , which improves the consistency by 85% compared to manual operation. In addition, the system integrates a 3D contour scanning module, which reconstructs the surface morphology of the workpiece through structured light projection and phase unwrapping algorithms, providing high-precision path planning data for the five axis linkage polishing robot, increasing the qualification rate of complex surface machining from 82% to 96%, significantly reducing post-processing costs.

## **4. Performance optimization and validation of low-cost visual inspection systems**

### **4.1. C++algorithm optimization practice**

In response to the strict real-time requirements of industrial scenarios, this study optimizes visual inspection algorithms at multiple levels based on the C++17 standard. In the image preprocessing stage, OpenCV's UMat class is used to implement GPU acceleration, and the Fourier transform operation time is compressed from 12.3 ms to 3.1 ms through the `cv::dft()` function. To address the redundancy problem of traditional Canny edge detection algorithms, non-maximum suppression parallelization transformation is introduced, and the OpenMP multi-threaded library is used to improve the efficiency of 8-neighborhood traversal by 4.2 times. In the feature extraction stage, SIFT feature point calculation was optimized through template specialization technology, increasing the keypoint detection speed from 15 fps to 28 fps while maintaining a 98.7% repeat detection rate. To address the bottleneck of deep learning inference, TensorRT quantization tool was used to compress the

MobileNetV3 model from FP32 accuracy to INT8, achieving a inference delay of 35.6 ms on NVIDIA Jetson TX2 edge devices, which is 3.8 times faster than the original framework. In addition, by using memory pooling technology to manage image buffers, the number of dynamic memory allocations is reduced, resulting in a memory fragmentation rate of less than 0.5% during continuous 10 hour operation of the system, significantly improving stability in industrial environments.

## 4.2. Testing strategy and quantitative indicators

To comprehensively evaluate system performance and construct a three-dimensional testing system that covers functionality, accuracy, and robustness. The functional testing adopts black box testing method, designing 20 typical industrial scenario test cases to verify the detection integrity of the system under extreme conditions. Precision testing constructs ground truth values through high-precision calibration plates and laser interferometers, quantifying the absolute error of the evaluation system in tasks such as pose estimation and defect localization. Robustness testing simulates environmental factors such as lighting fluctuations, vibration interference, and electromagnetic noise in industrial sites, and calculates the failure rate of the system under composite interference<sup>[5]</sup>. Specific quantitative indicators include: pose estimation repeatability, defect recognition recall rate, real-time processing frame rate MTBF. The test data collection adopts the NI PXIe data acquisition system, which synchronously records the visual output and standard equipment measurement values, ensuring that the spatiotemporal alignment accuracy of the data is better than 1 ms.

## 4.3. Experimental results and analysis

To verify the optimization effect, comparative experiments were conducted on the automotive parts production line. The testing system included both traditional and optimized low-cost solutions, with consistent experimental conditions. The experimental results are shown in **Table 1**.

**Table 1.** Performance comparison experimental data of visual inspection systems

| Test metrics                      | Traditional solution | Low cost optimization plan | Increase margin |
|-----------------------------------|----------------------|----------------------------|-----------------|
| Position estimation error (mm)    | 0.12 ± 0.03          | 0.08 ± 0.02                | 33.3%           |
| Defect recognition accuracy (%)   | 92.5                 | 96.8                       | 4.6%            |
| Single frame processing time (ms) | 45.2                 | 28.7                       | 36.5%           |
| Hardware cost (10000 yuan)        | 8.5                  | 2.3                        | 72.9%           |

Experimental data shows that the low-cost solution significantly improves processing efficiency and economy while maintaining industrial grade accuracy: the pose estimation error is reduced to 0.08 mm, meeting the requirements of precision assembly. The accuracy of defect recognition has been improved to 96.8%, reducing the missed detection rate by 62% compared to traditional methods; Single frame processing time compressed to 28.7 ms, achieving real-time performance of 34.8 fps. The hardware cost has decreased by 72.9%, and the investment payback period has been shortened to 8 months. Further analysis revealed that algorithm optimization contributed 42% of the performance improvement, with GPU acceleration and parallelization transformation accounting for the highest proportion. Hardware selection optimization contributed to a 58% cost reduction, mainly due to the cost-effectiveness advantage of domestic cameras. This experiment validates the technical feasibility of low-cost visual inspection systems in industrial scenarios, providing a quantitative reference for the intelligent

transformation of small and medium-sized enterprises.

## **5. Application cases and industry value analysis**

### **5.1. Electronic manufacturing industry: “Precision Revolution” in PCB defect detection**

In the production of PCB for 5G communication equipment, traditional manual visual inspection has pain points such as high missed detection rate and low efficiency, while the cost of imported AOI equipment is as high as 2 million yuan per set, which is difficult for small and medium-sized enterprises to afford. The low-cost visual inspection system developed in this study adopts an 8K line scanning camera and a multi-scale feature fusion algorithm, which can identify defects such as 0.02 mm level line short circuits and hole deviations. The detection accuracy reaches 99.2%, which is 12 times more efficient than manual detection. In the application of a leading PCB enterprise, the system adapts to the reflective characteristics of different board layers through dynamic threshold adjustment technology, reducing the over inspection rate from 15% to 3%, and saving over 3 million yuan in rework costs per line per year. This case demonstrates that low-cost visual inspection systems have achieved universal application of high-precision inspection technology through algorithm optimization and hardware selection innovation, helping electronic manufacturing move towards the goal of “zero defects”.

### **5.2. Automotive industry: The ‘Full Inspection Era’ of body welding**

The welding quality of car body in white directly affects the safety of the entire vehicle, and the traditional sampling mode has a 3% risk of defect omission. After introducing a low-cost visual inspection system, a joint venture car company deployed 12 industrial cameras at the welding station to monitor the position, penetration depth, and spatter defects of welding points in real time through stereo vision reconstruction technology, achieving 100% online full inspection. The system adopts a lightweight YOLOv5s model for defect classification, achieving an inference speed of 25 fps on NVIDIA Jetson AGX Xavier edge devices, which reduces energy consumption by 65% compared to traditional industrial computer solutions. Application data shows that the system has reduced the welding defect rate from 0.12% to 0.03%, avoiding recall losses of over 50 million yuan annually. At the same time, through closed-loop control of welding parameters, the comprehensive efficiency of equipment has been improved by 18%, promoting the automotive industry to enter a new stage of “full inspection + intelligent operation and maintenance”.

### **5.3. Food packaging industry: Quality upgrade from “Compliance” to “Traceability”**

The detection of foreign objects in food packaging must meet the strict standards of the HACCP system. Traditional X-ray detection equipment poses a risk of radiation leakage and is costly. The low-cost multimodal detection system developed in this study integrates visible light imaging and terahertz time-domain spectroscopy technology, which can penetrate aluminum foil packaging and identify 0.3 mm glass and metal fragments. The detection sensitivity is three times higher than that of a single sensor. In a dairy product enterprise application, the system uses blockchain technology to associate detection data with production batches, achieving “one item, one code” quality traceability, reducing product recall response time from 72 hours to 2 hours. In addition, the system adopts modular design, which can quickly switch detection models according to product lines, increasing the comprehensive utilization rate of equipment to 92%, shortening the investment return cycle by 60% compared to traditional specialized equipment, and promoting the transformation of the food packaging industry from “compliant production” to “active safety”.

## 5.4. Industry value summary

The core value of low-cost visual inspection systems lies in three aspects: technological inclusiveness, efficiency improvement, and industrial empowerment. At the technical level, through algorithm lightweighting and hardware localization, the cost of visual inspection can be reduced by more than 70%, enabling small and medium-sized enterprises to have intelligent transformation capabilities. On the efficiency level, achieving millisecond level response and micrometer level accuracy, promoting the upgrade of industrial inspection from “sampling inspection” to “full inspection” and from “post repair” to “process control”. At the industrial level, we will build a “perception decision execution” closed loop to help key industries such as electronic manufacturing and automotive industry improve product qualification rates by 3–5%, saving quality costs of over 10 billion yuan annually. According to statistics from the Ministry of Industry and Information Technology, the size of China’s industrial vision market will reach 18 billion yuan in 2023, with low-cost solutions accounting for over 40%, becoming a key driver for the popularization of intelligent manufacturing. In the future, with the integration of 5G and AIoT technologies, low-cost visual inspection systems will further expand to emerging scenarios such as flexible manufacturing and remote operation and maintenance, providing Chinese solutions for the transformation and upgrading of the global manufacturing industry.

## 6. Conclusion

Aiming at the technical bottleneck of low-cost visual inspection system, through C++ algorithm optimization, multimodal sensor fusion and edge computing architecture innovation, this research realized the collaborative optimization of detection accuracy, processing speed and hardware cost, and verified its technical feasibility and economic value in electronic manufacturing, automobile industry and other fields. The experimental results show that the system reduces hardware costs by more than 70% and improves processing efficiency by 35% while maintaining industrial grade detection accuracy, significantly promoting the universal application of visual inspection technology. Future research will focus on optimizing cross modal data fusion algorithms, breakthroughs in dynamic deployment technology for lightweight models, and the development of open detection platforms for flexible manufacturing scenarios, providing more universal solutions for the intelligent upgrading of the global manufacturing industry.

## Disclosure statement

The authors declare no conflict of interest.

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