

# Research on “Intelligence + Digitalization” of Transformer Yoke Insulation Production Unit

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**How to cite this paper:** Gu, L., Yan, Z.J., Xiao, R.Q., Zou, T. and Song, G.J. (2025) Research on “Intelligence + Digitalization” of Transformer Yoke Insulation Production Unit. *Open Journal of Applied Sciences*, 15, 2268-2276.

<https://doi.org/10.4236/ojapps.2025.158150>

**Received:** July 15, 2025

**Accepted:** August 10, 2025

**Published:** August 13, 2025

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## Abstract

Aiming at the three major pain points of low production efficiency, poor positioning accuracy, and insufficient quality inspection reliability in manual operations of transformer yoke insulation production units, this paper conducts research on intelligent and digital transformation. By building a manufacturing platform integrating industrial robots, PLC control, artificial intelligence vision systems, MES, and digital twin technology, a full-process technical closed-loop is realized: industrial robots collaborate with PLC modular programs to complete automated assembly; the vision system achieves millimeter-level positioning guidance and defect detection; the digital twin system based on PQ Factory supports virtual-real synchronous debugging and optimization; the Internet of Things and MES dashboards realize visual management and control of all production elements. The application shows that this scheme significantly improves assembly efficiency, positioning accuracy, and product qualification rate, providing a reusable intelligent transformation path for the manufacturing of core components in rail transit.

## Keywords

Intelligence, Digitalization, Production Unit, Yoke Insulation

## 1. Introduction

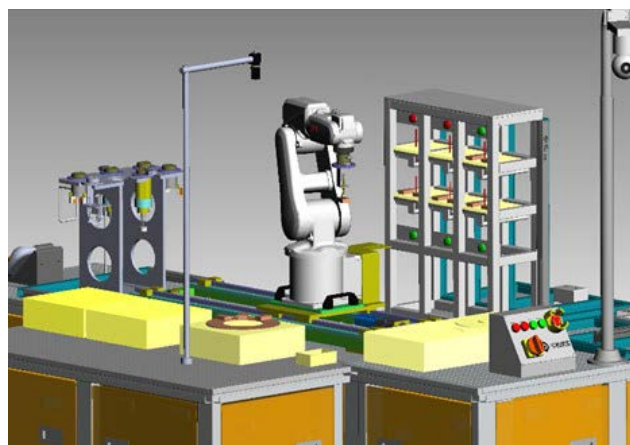
The report of the 20th National Congress of the Communist Party of China clearly proposes to “accelerate the building of a manufacturing powerhouse” and promote the high-end, intelligent, and green development of the manufacturing industry. By building smart factories and digital workshops, data-driven and flexible manufacturing in the entire production process can be realized, and efficiency and quality can be improved. Rail transit is a “strategic pillar” and “innovation engine” in China’s manufacturing system, and a core carrier for promoting the upgrading

of the industrial chain. As a core power equipment in rail transit, transformers will surely promote intelligent and digital transformation in the production process to achieve transformation and upgrading. Among them, the yoke insulation part is a key component of the transformer, installed at the upper and lower ends of the transformer coil, playing the role of oil conduction, mechanical support, and maintaining insulation distance. Its manufacturing precision, insulation performance, and consistency directly affect the safety and service life of the transformer. However, currently, the production of yoke insulation in the market is manual operation, which is characterized by low production efficiency, low positioning accuracy, and poor quality inspection effect. Therefore, exploring the research on “intelligence + digitalization” of transformer yoke insulation production units, developing an “intelligence + digitalization” manufacturing platform integrating “intelligent equipment, visual guidance, and virtual verification”, improving production efficiency [1], promoting the transformation of traditional manufacturing to intelligence and digitalization, and providing technical reference for related industries to realize intelligence + digitalization.

## 2. Overall Framework of “Intelligence + Digitalization” for Yoke Insulation Production Unit

This paper studies the yoke insulation production unit of transformers. The entire process of yoke insulation production is completed by robot operations, integrating visual intelligent assembly technology, visual inspection technology, digital twin technology, and MES technology to realize “intelligence + digitalization” production, and improve the qualification rate, consistency, and reliability of product quality.

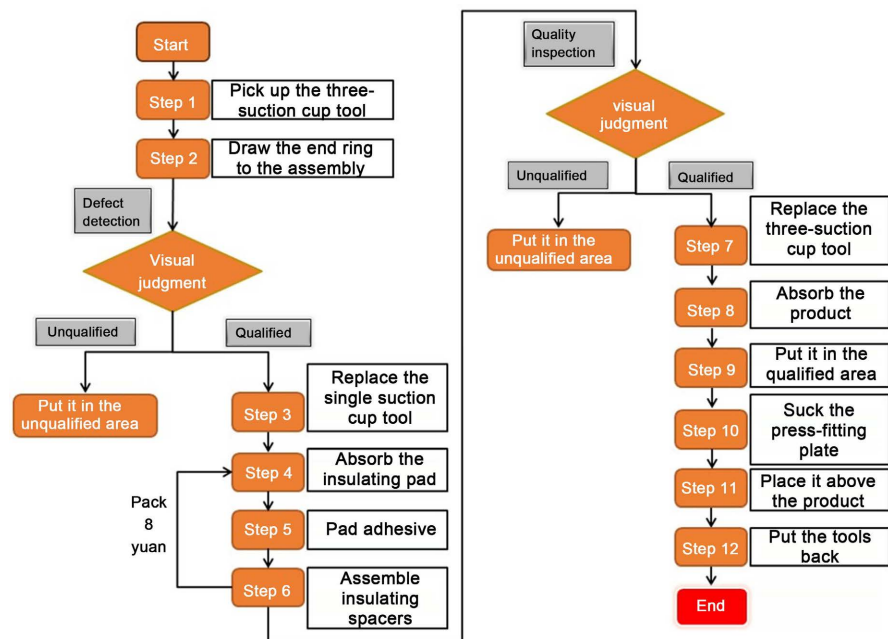
The hardware configuration and specific framework of “intelligence + digitalization” for the yoke insulation production unit are shown in **Figure 1**.



**Figure 1.** Hardware framework diagram.

The hardware components include a six-axis industrial robot, industrial-grade vision system, sensors, digital twin system, material storage unit, and tooling unit

supporting the robot. The workflow is as follows: the robot picks up a three-suction-cup tool, sucks the insulating end ring and places it on the inspection workbench; the robot replaces it with a single-suction-cup tool, sucks the insulating pad, dips it in glue, and places it on the insulating end ring. The position of the insulating pad is obtained by the vision system and sent to the robot. After completing the assembly of the insulating pad, product quality inspection is carried out through visual technology. If the product passes the inspection, the robot sucks the product and places it in the qualified area. Finally, the robot sucks the pressing tool and places it on the product to make the insulating end ring device firmer, and the robot returns the tool to the origin [2]. The specific workflow is shown in **Figure 2**.



**Figure 2.** Flowchart of insulating pad assembly.

### 3. Realization Technology of “Intelligence + Digitalization” for Yoke Insulation Production Unit

This paper studies the realization of intelligence and digitalization of the insulating pad production line, improves production efficiency, and eliminates manual operations; introduces industrial robots and PLC technology to realize intelligent assembly; introduces artificial intelligence visual guidance and quality inspection to improve assembly positioning accuracy and quality inspection effect; introduces digital twin technology, Internet of Things, and MES technology to realize virtual-real interaction of the production line and visual display of production [3].

#### 3.1. Based on Industrial Robot and PLC Program Development Technology

In the field of industrial robot and Programmable Logic Controller (PLC) pro-

gram development, this paper focuses on the key technology realization of intelligent assembly process for insulating parts. The research adopts the collaborative development of RAPID advanced programming language dedicated to industrial robots and Ladder Diagram (LAD) language widely used in PLC, with the core being the implementation of a modular program design strategy [4]. This strategy decomposes the complex assembly process into logically independent units with clear interfaces (such as material grabbing, precise gluing, pad assembly, quality inspection, etc.), significantly improving code reusability, maintainability, and overall system reliability. Through rigorous program design and debugging, seamless collaboration between the industrial robot body and key peripheral equipment such as the storage unit, tooling unit, and vision system is ensured, strictly following the specific production process and rhythm requirements of insulating parts, thereby realizing efficient, orderly, and stable completion of the entire intelligent assembly operation [5].

Practical applications show that this integrated modular program design scheme has achieved significant results: on the one hand, by optimizing the robot's motion trajectory, reducing empty strokes, and precisely controlling the rhythm, the overall assembly efficiency and production capacity are effectively improved; therefore, this paper not only provides an efficient and reliable automated solution for insulating part assembly but also offers useful technical references and practical examples for the intelligent upgrading and green and sustainable development of related manufacturing industries.

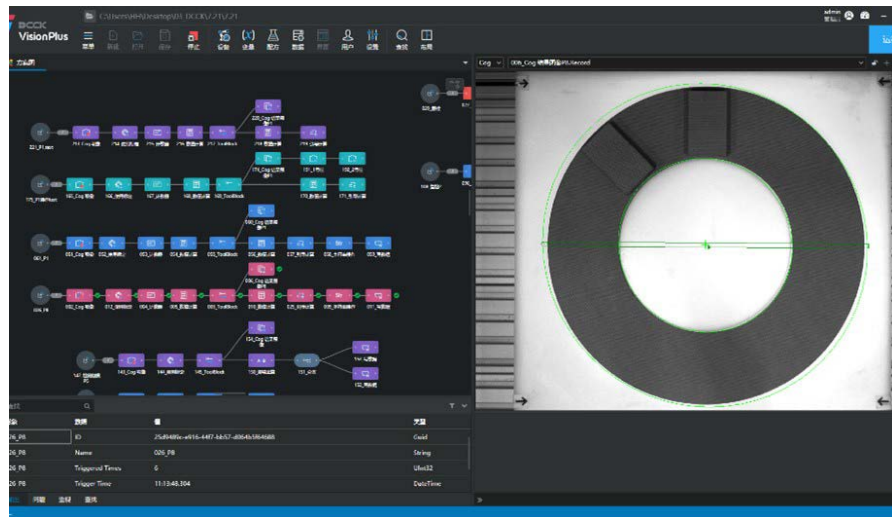
### **3.2. Based on Artificial Intelligence Visual Guidance Technology**

This paper deeply integrates advanced artificial intelligence technology, deep learning, and intelligent algorithms to build a powerful artificial intelligence visual guidance system. The system uses high-resolution cameras to capture product images and runs complex image processing and analysis algorithms to realize intelligent control, accurately realizing automatic identification of scratches on the surface of insulating end rings and high-precision spatial positioning and motion guidance of yoke insulating parts. Based on this real-time visual feedback, the software system precisely controls the robot to drive the intelligent assembly process of insulating pads, fundamentally solving the pain point of low positioning accuracy of pads in traditional assembly and providing core guarantee for achieving 100% product qualification rate. The software control system ensures the accuracy and efficiency of the entire intelligent assembly process, significantly optimizing the production process and improving product quality. The assembly result is shown in **Figure 3**.

### **3.3. Based on Visual Quality Inspection Technology**

In modern intelligent assembly systems, the stability and consistency of product quality are key to core competitiveness. Aiming at the pain points of traditional manual quality inspection methods, such as low efficiency, easy fatigue, incon-

sistent standards, and difficulty in covering all subtle defects, we take the lead in introducing and deeply applying advanced visual quality inspection technology as a key link to ensure the final product quality.



**Figure 3.** Schematic diagram of insulating pad assembly.

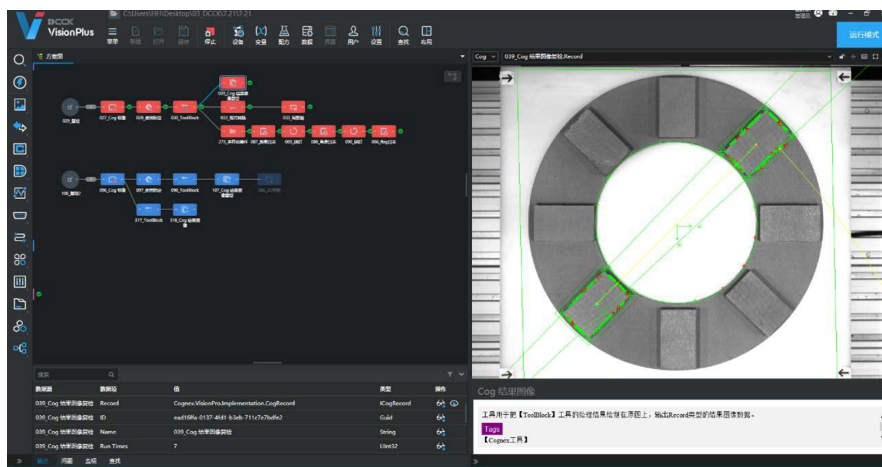
The core of the visual quality inspection technology system studied in this paper lies in the integration of cutting-edge machine vision hardware and powerful image processing algorithms. High-resolution, high-frame-rate industrial cameras are deployed, combined with precision lighting systems, to collect multi-angle and all-round images of the assembled insulating pads at key stations of the assembly line. These original image data are transmitted to the background processing unit in real-time.

The processing unit runs developed or optimized image recognition and processing algorithms. These algorithms have strong capabilities, as follows:

- 1) Precise positioning and segmentation: quickly identify the main body of the insulating pad in the image and its key feature areas.
- 2) Dimensional and geometric accuracy detection: automatically measure key dimensions, including the length and position geometric parameters between diagonal pads, and compare them with preset strict tolerance ranges.
- 3) Surface defect identification: efficiently detect various surface and appearance defects such as scratches, pits, burrs, stains, cracks, material defects, assembly misalignment, and foreign object residues [6].
- 4) Integrity verification: confirm whether the components are complete, and whether there are missing or wrong parts.

The entire inspection process achieves a high degree of automation and real-time performance. The system can complete the quality inspection of a single insulating pad within milliseconds and immediately make a “qualified” or “unqualified” judgment according to preset quality criteria that meet strict industry standards. Unqualified products will be automatically marked or trigger a rejection de-

vice to ensure they do not flow into subsequent processes. The inspection result is shown in **Figure 4**.



**Figure 4.** Schematic diagram of insulation spacer inspection.

### 3.4. Based on PQ Factory Digital Twin Technology

To effectively solve the production efficiency bottlenecks caused by complex debugging, high trial-and-error costs, and difficult optimization of production rhythm in the yoke insulation manufacturing process, this paper innovatively introduces digital twin technology to build a highly simulated virtual manufacturing platform.

Based on PQ Factory software, a virtual mirror system for all elements of yoke insulation manufacturing that strictly corresponds to the physical production line is built. This virtual system accurately simulates the motion logic of robots, working status of equipment, material flow paths, and the entire production process in the physical production line, laying a solid foundation for subsequent virtual debugging, process simulation, and optimization analysis.

To achieve seamless connection and real-time interaction between the virtual and physical worlds, this paper establishes a key data bridge through KingIO Server software. In this software environment, all key variables are precisely defined and mapped, including sensor signals, equipment status bits, robot control commands, process parameters, etc. This ensures that every important action and state change in the physical production line can be reflected in the virtual system in milliseconds; at the same time, parameter adjustments, program modifications, or simulated operation commands made in the virtual system can also be issued to corresponding physical equipment in real-time and accurately. This two-way, real-time data interaction mechanism is the core guarantee for achieving “virtual-real synchronization”, making the virtual system no longer a static model but a dynamic digital nerve center that “breathes and shares a common fate” with the physical production line [7].

The application of this digital twin platform has brought significant efficiency

improvements.

1) Virtual debugging and pre-verification: new programs, new processes, or equipment transformation schemes can be fully tested and optimized in the virtual environment first, greatly reducing on-site downtime for debugging, and lowering trial-and-error risks and costs.

2) Real-time monitoring and optimization of production processes: by mapping the status of the physical production line in real-time through the virtual system, managers can intuitively insight into bottleneck workstations, equipment efficiency, rhythm matching, etc., quickly locate problems and optimize parameters online, and improve overall equipment efficiency (OEE) [8].

3) Personnel training and scheme evaluation: new employee operation training or simulation and evaluation of various production schemes can be carried out in a safe and zero-loss virtual environment.

### 3.5. Based on Internet of Things and MES Technology

To solve the efficiency bottlenecks caused by opaque production status and delayed management response in yoke insulation manufacturing, this research deeply integrates Internet of Things (IoT) technology and Manufacturing Execution System (MES), uses HTML + CSS + JavaScript three web development languages to write programs, designs and implements a real-time, visual intelligent manufacturing management platform, which can collect and monitor data such as production progress and equipment status during system operation in real-time. The system architecture and technical implementation are as follows:

1) Data perception layer: through the deployment of sensors, PLC communication modules, and equipment interfaces, real-time collection of key data such as production line equipment status (such as standby, running, fault, etc.) and production progress (process completion quantity, qualified product rate).

2) System core layer: build a central database and business logic engine based on MES, integrate modules such as production planning, equipment management, and quality traceability to realize full-process digital management and control.

3) Visual interaction layer: use HTML5 + CSS3 + JavaScript front-end technology stack to develop dynamic dashboards, support multi-terminal adaptive display, and ensure the real-time and interactive friendliness of data presentation [9].

This research realizes dynamic mapping of the global status of the production line, displays key indicators such as equipment OEE, order completion progress, and abnormal alarms through multi-dimensional forms such as heat maps, trend curves, and Gantt charts, supports online ordering and process route binding, automatically associates detection equipment data, and realizes full life cycle traceability of products. The specific visual platform is shown in **Figure 5**.



Figure 5. Schematic diagram of visual platform.

## 4. Conclusion

This research focuses on the three major pain points of low production efficiency, poor positioning accuracy, and insufficient quality inspection reliability in traditional manual operations of transformer yoke insulation parts, and constructs an “intelligence + digitalization” manufacturing platform integrating intelligent equipment, visual guidance, virtual verification, and data-driven. Through the modular collaborative control of industrial robots (RAPID language) and PLC (ladder diagram), the full-process automated assembly of insulating end rings and pads is realized, the motion trajectory and rhythm control are optimized, and the assembly efficiency is improved; integrating artificial intelligence vision technology, using deep learning algorithms to complete millimeter-level spatial positioning and millisecond-level surface defect detection (scratch recognition accuracy  $\leq 0.1$  mm), 100% full inspection, ensuring 100% product qualification rate; building a digital twin system based on PQ Factory and KingIO Server, realizing two-way real-time synchronization between the physical production line and the virtual model, supporting virtual debugging and parameter pre-optimization; relying on the IoT sensor network and MES system, developing HTML5/CSS3/JavaScript cross-platform visual dashboards, dynamically monitoring equipment OEE, order progress, and quality traceability data. Empirical evidence shows that the production unit through Full-process technical closed-loop of “robot execution-visual guidance-twin optimization-MES management and control” significantly improves product quality stability and manufacturing flexibility, provides a reusable intelligent transformation path for the manufacturing of core components in rail transit, and has promotion value in the field of high-end insulating parts such as motors and capacitors.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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