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Optimization of soldering quality using Poka-Yoke and camera-based inspection to prevent incomplete production cycle: a case study in automotive stator assembly

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Abstract

This study was conducted at a manufacturing company located in Indonesia that produces Alternating Current Generator Starters (ACGS). In the ACGS production process, there is a solder inspection stage that was previously performed manually by operators. The main issue encountered is incomplete production cycles, a condition where a production cycle is not fully completed, but the product continues to the next stage, increasing the risk of undetected defective or rejected products. Research aims to design a camera check system that integrates the Poka-Yoke method to enhance accuracy and prevent errors caused by human factors based on continuous improvement through the Plan, Do, Check, Action (PDCA) cycle. This study compares two camera inspection programs: program model 1, with individual position calibration per solder point, and program model 2, with a shared calibration setup, to evaluate inspection effectiveness. The quantitative comparative testing results show a detection accuracy of up to 99.92% and an inspection result classification accuracy reached 99.73%, indicating a significant improvement in the reliability of the visual inspection system and quality assurance for soldering results in industry.

Keywords:
Camera check, inspection, jumping process, Poka-Yoke, solder defect.

1 Introduction

A manufacturing company that produces components for two-wheeled and four-wheeled vehicles, with one of its products being the Alternating Current Generator Starter (ACGS) or referred to by another name, Integrated Starter Generator (ISG). ACGS is a component in two-wheeled vehicles that functions as a starter for internal combustion engines and serves as the primary electrical power generator [1], [2]. The production process of the ACGS component involves two main components: rotor assembly and stator assembly. In the production of the stator assembly, there is an inspection process for the soldering quality between the armature assembly, known as the core of stator components, which contains a wire copper coil, and the wire assembly, the sub-assembly consists of wire and a connector [3]. Three wires need to be checked for proper connections. The soldering process involves the addition of a filler material, typically tin, under various conditions, such as Fig. 1.

A recurring issue is the potential for incomplete production cycles, in which a product proceeds to a subsequent stage of production without having completed all or part of a previous process. This issue can adversely affect component functionality and lead to customer claims regarding product non-conformities. Although such occurrences may not happen frequently, they can be prevented through the implementation of the Poka-Yoke method, a technique that prevents mistakes, or, according to others, it is a solution that allows for the discovery and correction of mistakes that have already occurred [4], [5], [6].

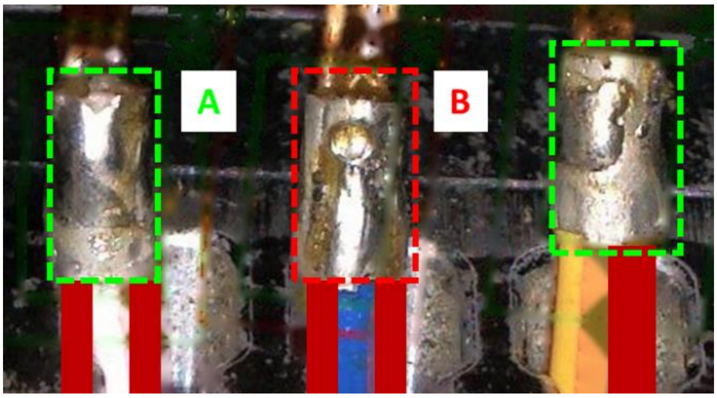


Fig. 1. Differences in normal (A) and abnormal (B) solder conditions.

Defective solder joints may cause electrical flow disturbances, reduced conductivity, and total failure of electronic component functions, especially when left undetected during the early stages of production [7]. This has become critical in industries requiring high reliability, such as the automotive component industry, where solder failures may result in safety risks and severe damage [8]. Poor bonding between the solder and the metal surface can lead to overheating, reduced insulation strength, accelerated component degradation, and increased risk of cable or interconnection failures [9].

Manual inspection methods for soldering often result in detection errors of 20–30% due to operator fatigue, subjectivity, and variability in experience [9]. Quality inspection involves a human operator who inspects the product to ascertain its conformity. However, the accuracy and reliability of the inspection are often unsatisfactory. Operator accuracy in detecting rejected parts manufactured with precision reaches 85%, while the industry average is 80%, indicating that 15-20% of defective products may escape detection during manual inspection [10].

Advancements in computer vision have transformed visual inspection into the mainstream methodology for quality control [11]. One of the solutions to prevent faulty products, besides sampling products and inspecting them manually, is to visually inspect the parts also in the final stage of production [12]. Machine vision technology is needed to substitute for manual detection. It can not only avoid the occurrence of missed detection in manual detection, but also improve the detection efficiency [13].

The limited implementation and evaluation of automated soldering inspection camera-based systems integrated with the Poka-Yoke method to prevent both incomplete production cycles and the escape of defective products while reducing operator-induced errors constitutes a critical unresolved issue. Therefore, the novelty of this research lies in integrating Poka-Yoke methods with a camera-based inspection system to improve solder joint quality and prevent incomplete production cycles in automotive stator assembly lines, with validation through direct testing and a quantitative comparative analysis before and after implementation, therefore demonstrating the system's effectiveness in real industrial practice.

2 Research methodology

A case study approach based on actual issues identified in the industry, particularly concerning the quality of soldering processes. To address these challenges, an improvement initiative was undertaken by integrating an automated camera-based inspection system with the Poka-Yoke method, with an error-proofing technique designed to eliminate mistakes caused by human intervention/human error [14]. The improvement strategy was structured using a continuous improvement methodology that follows the Plan, Do, Check, Action (PDCA) cycle, a well-established framework for quality management [15].

This systematic approach includes comprehensive phases, such as a plan performed by a Pareto diagram based on previous issues until reaching detailed root cause analysis and design development of the inspection system to be implemented. The second stage is doing an improvement plan on the production line, such as installation of hardware and software to implement the improvement plan, followed by testing and process monitoring. During the monitoring process, changes were made based on data collection and presented in a graph to analyze problem-solving during monitoring. Standardization is performed after all objectives are completed, such as rejected detection and error classification ratio below the specified limit, and the last step is the evaluation of the results. The entire process is visually represented in the flow diagram shown in Fig. 2.

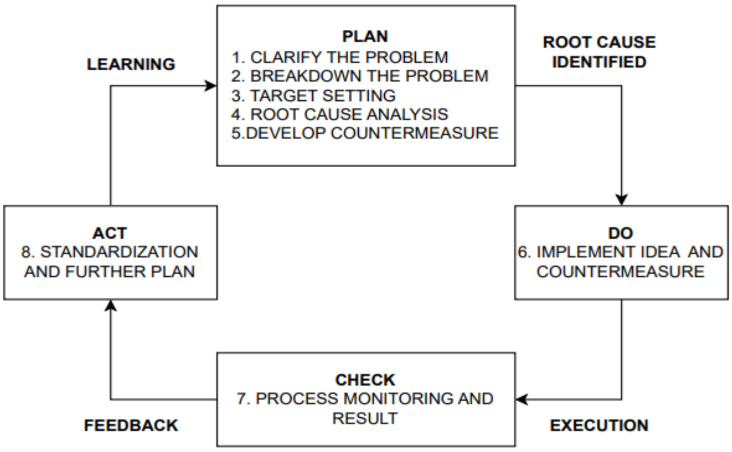


Fig. 2. PDCA cycle.

Outcomes of this study include the design and installation of the camera-based inspection system, as well as detailed insights gained from testing and experimental activities. These activities were conducted to improve inspection accuracy and minimize errors by optimizing the performance of both the camera hardware and the IV3-Navigator software, which is the default data processing tool provided by KEYENCE. The findings highlight the importance of precise system configuration and software settings for experimental use in achieving stable and accurate detection results, particularly in a high-demand industrial production environment.

2.1 Research design

The research design is structured to achieve the objective of improving solder inspection quality during the wire-connecting soldering process in the stator assembly, with the key activities including: (1) create a list of tools and components requirements (Table 1) for the inspection system to function properly, with diagrams of component installation in Fig. 5. (2) Performed tests and experimental studies on IV3-navigator program settings to improve the accuracy and reliability of camera-based inspection systems.

These components work together to control the movement of the pallet based on the inspection outcome. When the product is evaluated as OK, the Lift Stopper Mechanism is activated to move to a lower position, allowing the pallet and the inspected product to proceed to the next stage of the production process without interruption. In other conditions, if the product is classified as Not Good (NG), the actuator holds the Lift Stopper in the upper position, preventing the pallet carrying product from passing through to the next process. This mechanism ensures that defective products do not proceed to the following process stage and are marked for removal from the production flow. Therefore, this contributes to improved quality control and reduces the risk of defective units reaching end users.

Table 1. Additional components

Component	Specification
Camera check sensor	Keyence IV3-G500CA
Photoelectric sensor	Keyence LR-X250
Personal computer CPU + monitor	ASUS NUC 12 Intel Core i5 + monitor
Programmable logic components	OMRON PLC
Human machine interface	OMRON HMI NB series
Pneumatics actuator	SMC 20 mm stroke
Master valve	SMC soft start 1/4
Anti-back unit	Manufactured
Lift stopper mechanism	Manufactured

Two program models were developed to improve detection accuracy. Model 1 used individual position adjustments for each solder point as shown in Fig. 3. This configuration was implemented from October 11 to November 18, 2024, operating 24 hours a day over five workdays per week.

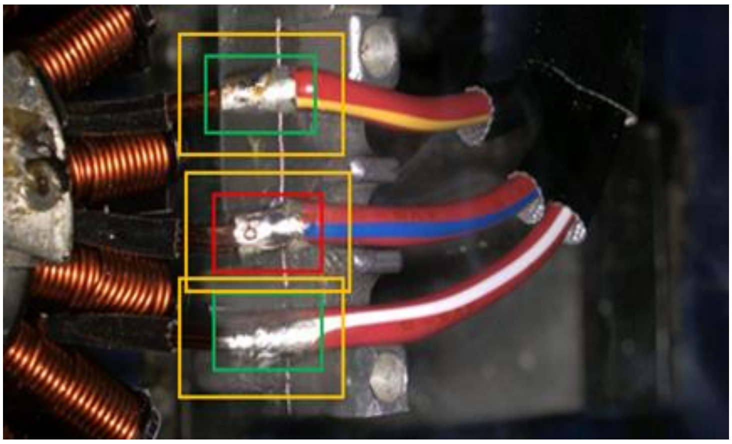


Fig. 3. Program model 1.

Program model 2, implemented from November 19 to December 31, 2024, the system used a single position adjustment shared across all three solder points shown in Fig. 4. This model aimed to simplify positional calibration and enhance detection efficiency within a single inspection cycle. Both models (program model 1 and program model 2) were tested and compared to evaluate their performance in accurately detecting solder positions. Detection accuracy results (Table 2) and classification performance for OK and NG categories (Table 3**).** The comparison highlights the strengths and limitations of each configuration in applying a camera-based visual inspection system.

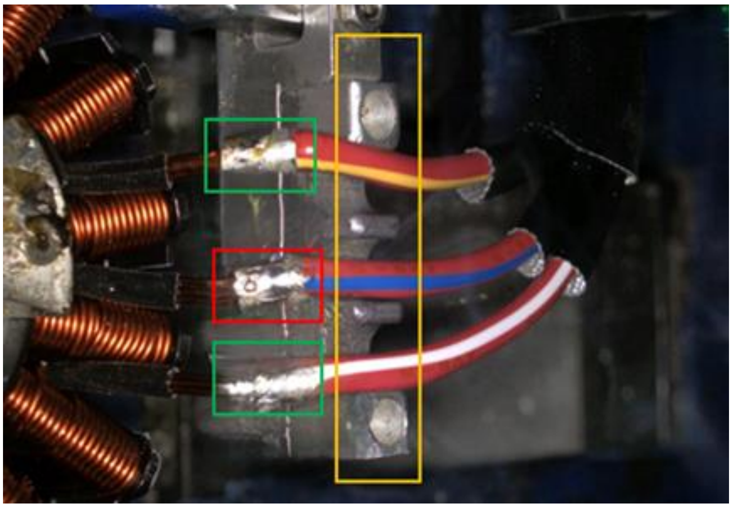


Fig. 4. Program model 2.

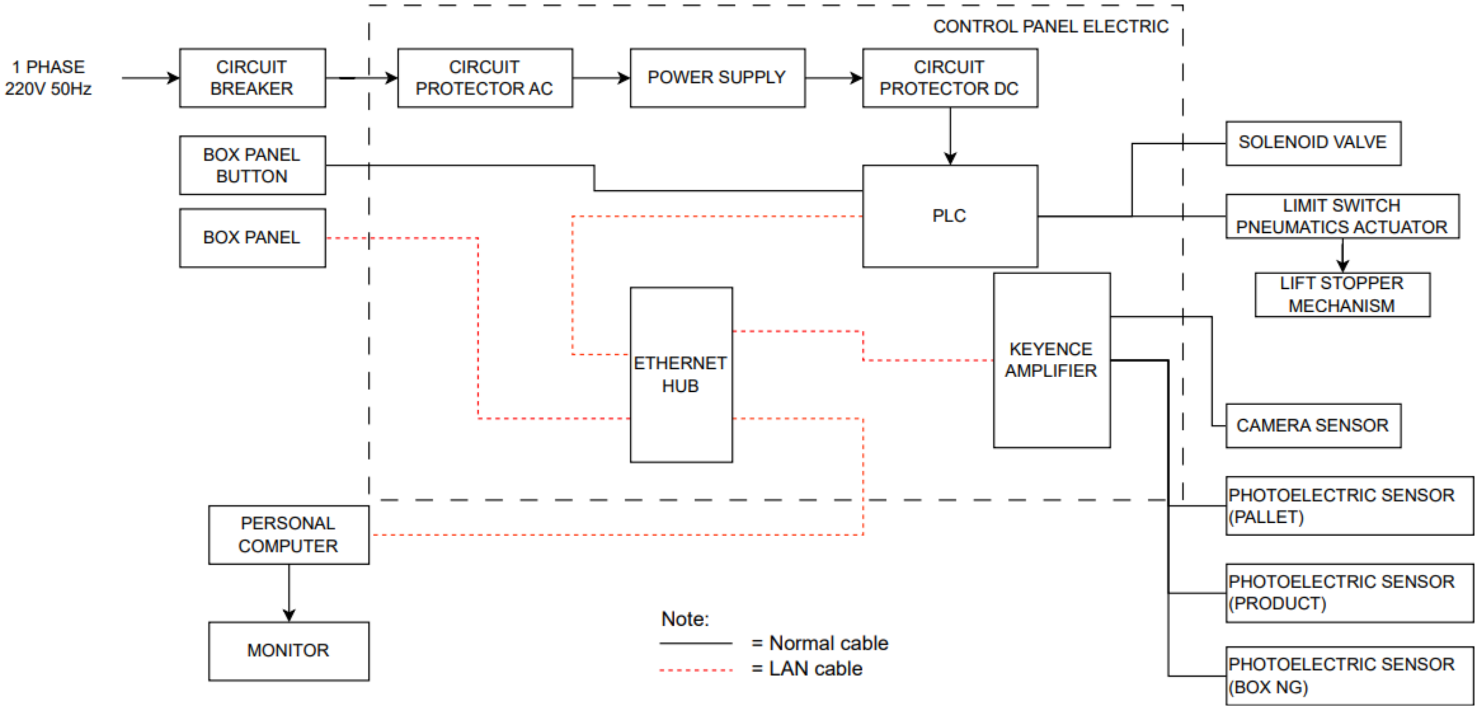


Fig. 5. Diagram of installation components.

2.2 Data collection and analysis methods

The testing method used is comparative testing. This involves evaluating the system's performance after the implementation of the camera check and Poka-Yoke method. The parameters evaluated include: (1) accuracy in detecting solder positions, (2) accuracy in classifying OK or NG products.

Data was collected from continuous production over three months (October–December 2024), using total sampling from two shifts per day (morning and evening), covering five working days per week. Quantitative data sampling every day is saved on a computer by Keyence IV3 Navigator software, which is a built-in application of the camera sensor used with AI-based object recognition of soldering conditions. From the quantitative data, calculations were made on False Reject Rate (FRR) to calculate detection accuracy and classification accuracy using Eq. (1), where N_{FR} is the number of false rejects/errors and N_{match} is the total number of samples and False Accept Rate (FAR), where N_{FA} is the number of false accepts and $N_{nonmatch}$ is the total number of non-matching samples using Eq. (2).

$$FRR = \frac{N_{FR}}{N_{match}} \tag{1}$$

$$FAR = \frac{N_{FA}}{N_{nonmatch}} \tag{2}$$

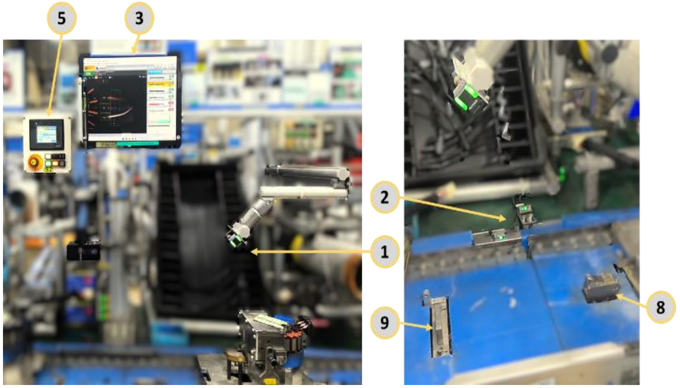
FRR and FAR data in the form of percentages are used as input data for a two-sample t-test with equal variances. The Student's t test (also called the T test) is used to compare the means between two groups, and there is no need for multiple comparisons, as a unique P value is observed [16].

Comparative testing was conducted using two different detection system models; each configured using the available features within the IV3-Navigator software. This approach was taken to evaluate and compare the effectiveness, precision, and overall stability of each model in detecting soldering points under real production conditions. The primary objective of the testing was not only to measure the system's accuracy in identifying the presence and position of soldering objects, but also to assess its capability in minimizing inspection errors and, particularly, misjudgments that could result in defective products passing undetected. Results from this comparison serve as a critical fundamental for selecting the most suitable inspection configuration to be implemented on the production line.

3 Results and discussion

3.1 Hardware implementation

Following the observation activity on the production line and the further design development, data were obtained to identify the required components for the integration of a camera-based inspection system with the Poka-Yoke method. The additional components (Table 1) and the installation locations are shown in Fig. 6, and supporting components such as the pneumatic actuator and master valve are shown in Fig. 7. However, some components are hidden. For example, Programmable Logic Controller (PLC) is installed in the control electronics.



(a) (b)

Fig. 6. Installation location for additional components.

The camera check sensor functions as the primary sensor in the system, effectively replacing the manual inspection process previously performed by the operator. This sensor captures images of the soldering area, and the data is then processed using the IV3-Navigator software installed on a computer. The inspection results are visually displayed on a monitor for real-time monitoring and verification, as illustrated in Fig. 6, section (a). Output data generated by IV3-Navigator also acts as a control input for the PLC, which subsequently sends commands to the actuator and the Lift Stopper Mechanism.

Three photoelectric sensors were added, shown in Fig. 6, section (b), component number 2, each serving to detect the presence of a product-carrying pallet, the product itself, and the reject box, which collects defective products. The anti-back unit was installed to prevent rejected products from returning to the previous process, which may potentially bottleneck may be occur on the production line.

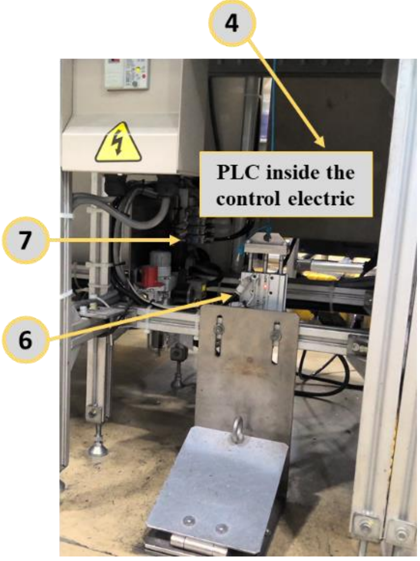


Fig. 7. Installation of PLC and pneumatic components.

Human Machine Interface (HMI) is used for configuring the operation of the automated system and also allows manual control of components such as the pneumatic actuator during troubleshooting. After completing the installation, a functional test was conducted to ensure the camera inspection system could accurately detect the soldering object.

3.2 Performance testing: model 1 vs. model 2

An issue was identified in the accuracy of the solder object detection camera-based inspection system and the Poka-Yoke method while operating. Errors generated by the camera check system, such as misclassification of detection results (misjudgment) due to poor contrast, glare, or inconsistent solder appearance. Failure to detect soldering objects (misposition) due to mechanical vibration and variation in product alignment. Disruptions caused by environmental factors (misdetection), camera latency, lighting fluctuations, and sensor limitations are collectively referred to as detection errors (error judgment). All error judgments distributed (Table 2) will affect the percentage value in detection and classification accuracy.

Comparative testing between program model 1 and model 2 (Table 3) revealed that detection accuracy and classification accuracy (Table 4) improved significantly under program model 2. During monitoring, most errors were found in OK products incorrectly classified as NG (FRR), whereas FAR was negligible. This indicates that the system configuration directly influences inspection stability and accuracy. Similar outcomes were reported by [12], who highlighted that optimized AI-based visual inspection can significantly reduce false rejects in high-volume manufacturing environments.

Table 2. Error type distribution

Program model	Misjudgement	Misposition	Misdetect
Model 1	35.17%	36.50%	28.33%
Model 2	23.12%	16.76%	60.12%

Table 3. Detection accuracy

Program model	Number of samples	Number of errors	Accuracy
Model 1	46186	170	99.63%
Model 2	49782	40	99.92%

Table 4. Classification accuracy with FRR

Program model	Number of samples	Number of errors	FRR
Model 1	46186	430	0.93%
Model 2	49782	133	0.27%

Statistical analysis also demonstrated the superiority of program model 2. As illustrated in Fig. 8, error rates dropped sharply within one day of implementation, and t-test analysis confirmed that the difference between the two models was statistically significant ($p < 0.05$, Table 5 and Fig. 9). This result corroborates earlier research by [16] and [17], who emphasized the importance of statistical validation when assessing inspection system improvements.

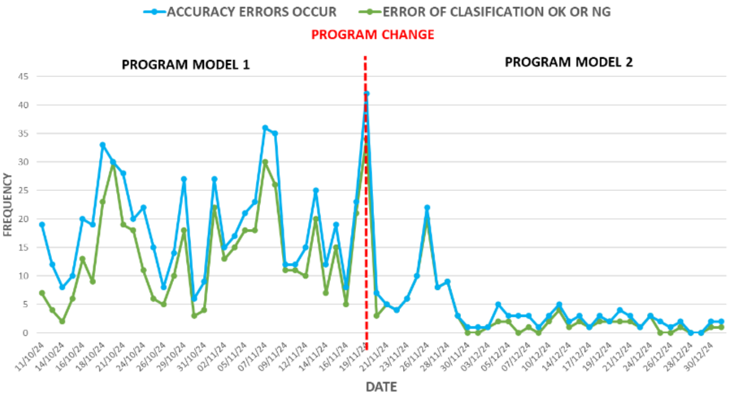


Fig. 8. Daily error monitoring graph during model 1 and model 2 implementation

Table 5. T-test result: two-sample assuming equal variances

	Model 1	Model 2
Mean	1.666%	0.882%
Variance	8.6245E-05	2.72055E-05
Observations	32	36
Pooled variance	5.49361E-05	
Hypothesized mean difference	0	
df	66	
t Stat	4.353349021	
P(T<=t) one-tail	2.38533E-05	
t Critical one-tail	1.668270514	
P(T<=t) two-tail	4.77065E-05	
t Critical two-tail	1.996564419	

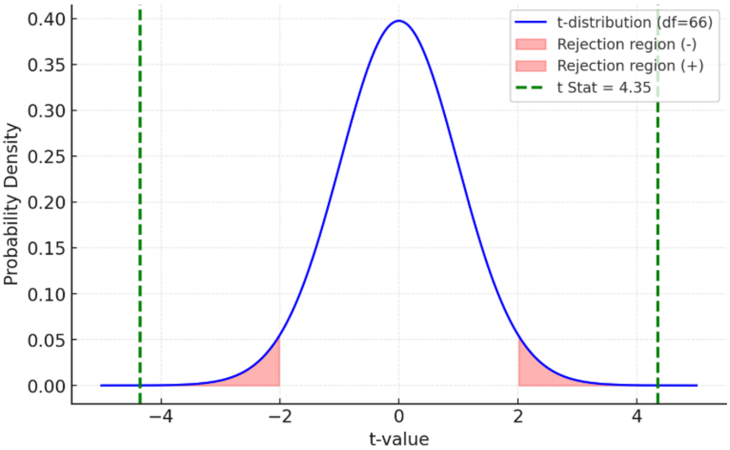


Fig. 9. Bell curve two-sample model t-test.

3.3 Error analysis and optimization insights

These errors can significantly affect the accuracy and reliability of the inspection process, potentially allowing defective products to pass undetected or causing false rejections of acceptable items, with the potential reducing operation ratio from production output.

The Fault Tree Analysis (FTA) in Fig. 10 illustrates potential causes of error judgment in vision inspection systems. Misjudgment often arises from brightness and focus adjustment issues or improper learning settings; misposition results from inaccurate object alignment or calibration; and misdetection may be caused by improper trigger delay or unstable environmental factors. Similar error classifications have been widely documented in previous studies on automated inspection systems [13] [9]. These studies also highlight that continuous optimization of lighting, calibration, and algorithm configuration is essential to reduce error rates.

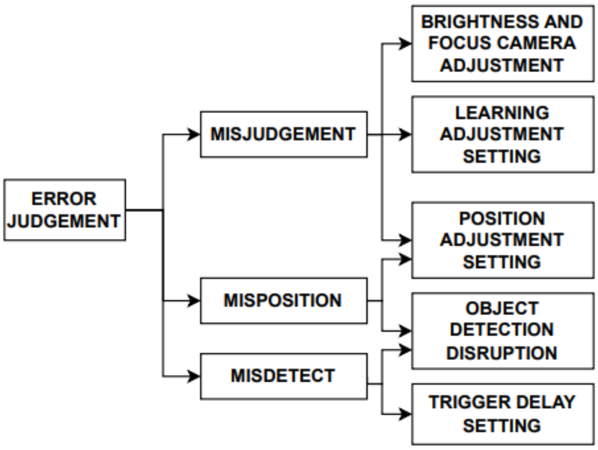


Fig. 10. Fault tree analysis of error judgement.

The integration of camera-based inspection and Poka-Yoke methods significantly improved the accuracy and reliability of solder joint inspection. A comparison between program model 1 and model 2 demonstrated that proper system configuration plays a critical role in minimizing detection and classification errors. These improvements not only enhance inspection performance but also support continuous quality assurance efforts to maintain the quality of products issued in order to improve the company's product reputation and increase competitiveness in the automotive manufacturing industry.

The integration of camera-based inspection with Poka-Yoke methods in this study significantly enhanced solder joint quality inspection. Compared to program model 1, program model 2 achieved higher detection accuracy and more consistent performance, reinforcing the importance of precise system configuration in minimizing detection and classification errors. This is consistent with prior research demonstrating that combining error-proofing methods with AI-based inspection improves both process reliability and product quality in industrial applications [4] [6] [8].

These improvements not only enhance inspection performance but also contribute to continuous quality assurance and competitiveness in the automotive manufacturing industry.

4 Conclusions

This study introduces a novel approach by integrating poka-yoke principles with AI-based camera inspection to error-proof soldering operations, offering a clear advancement over existing manual or single-technology inspection methods. The system's industrial applicability has been validated through real-case implementation on an automotive component manufacturing line, showing its potential for scalability while significantly reducing inspection error rates and improving product quality assurance. Program model 2 with accuracy detection at 99.92% and classification accuracy at 99.73%, proved to be significantly more effective and reliable than program model 1 in minimizing error judgments, reinforced by the t-test result. Single position adjustment for all three solder points in model 2 resulted in improved imaging and more precise focus. The system improves accuracy, saves time on inspection, prevents defects, and offers high adaptability. Future work to refine this research should explore areas such as multipoint/3D inspection, adaptive learning, and cross-sector cost–benefit evaluation.

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