JURNAL TEKNIK MESIN DAN MEKATRONIKA
Journal of Mechanical Engineering and Mechatronics
ISSN: 2527-6212, Vol. 11 No. 1, pp. 01 - 14

Analysis of TC_INNEST Alarm on FANUC M-900iA Multigun Welding Robot System

Firman Davidsyah Adam[1,a], Rahmat[2,b]

[1,2]Department of Mechanical Engineering, Universitas Sains Indonesia, West Cikarang, Bekasi, West Java 17530, Indonesia

[a]firmandavidsyah21@gmail.com (corresponding author), [b]rahmat.r@lecturer.sains.ac.id

Abstract
Industrial welding robots are critical assets in automotive manufacturing, where high system reliability is essential to maintain production continuity and minimize downtime. This study investigates the recurring TC_INNEST alarm in a FANUC M-900iA multigun welding robot equipped with dual welding guns. The alarm consistently occurred during the automatic gun-changing sequence, particularly when the robot returned to the home position after releasing the first welding gun and before engaging the second gun. Field observations showed that the alarm occurred more than 10 times per production shift, resulting in approximately 1–3 minutes of downtime per occurrence. Based on direct field observations, technical inspections, and maintenance analysis, the alarm was associated with communication instability and interlock disturbances involving the DeviceNet communication system, communication cables, sola cables, and the robot controller. Initial corrective actions, including controller reset and temporary plug-and-play reconnection, restored robot operation but failed to eliminate the root cause. Comprehensive corrective maintenance, including communication cable replacement, controller inspection, motherboard cleaning, and replacement of internal communication cables, successfully eliminated the recurring alarm. The findings indicate that degradation of communication components and contamination inside the controller significantly affected communication reliability during the automatic tool-changing process. Overall, no recurrence of the TC_INNEST alarm was observed during subsequent production, demonstrating the effectiveness of the proposed maintenance strategy for improving robot reliability and reducing production downtime.

Keywords: Downtime reduction; FANUC M-900iA; Multigun welding; Preventive maintenance; Robots; TC_INNEST alarm.

I. Introduction

I.I. Background

The automotive manufacturing industry increasingly relies on industrial automation to achieve high productivity, product quality, and operational efficiency. Among various automated technologies, industrial welding robots have become indispensable for resistance spot welding processes because they provide high precision, repeatability, and production consistency [1]. As vehicle production volumes continue to increase, maintaining the operational reliability of welding robots has become one of the key factors affecting manufacturing performance [2]. Any interruption in robot operation may reduce production efficiency, increase downtime, and consequently affect production targets and operational costs [3].

The FANUC M-900iA is one of the industrial robots widely used in automotive body shop production lines for resistance spot welding applications. To improve manufacturing flexibility and equipment utilization, this robot is commonly integrated with a multigun welding system that automatically changes welding guns using a tool changer mechanism. Although this configuration improves production efficiency, it also increases the complexity of communication, interlock verification, and synchronization between the robot controller and peripheral devices [4]. Industrial robots consist of multiple mechanical and electrical components whose reliability directly affects production continuity. Continuous health monitoring and prognostics are therefore necessary to minimize unexpected equipment failures [5].

Reliable communication between the robot controller, DeviceNet network, welding gun system, and field devices is essential to ensure safe and continuous robot operation. In robotic spot-welding systems, production interruptions are commonly associated with contamination, communication failures, hardware degradation, and unexpected equipment behavior. Identifying the correlation between these failures is essential for performing effective root cause analysis and preventing production downtime [6]. Communication failures, interlock errors, or synchronization problems during the tool-changing sequence may interrupt the welding cycle and trigger abnormal robot alarms, leading to production downtime and maintenance intervention [7].

One of the recurring operational problems observed in the automotive manufacturing company investigated in this study is the occurrence of the TC_INNEST (Tool Change Inner Nest) alarm on the FANUC M-900iA multigun welding robot. The alarm repeatedly appeared when the robot returned to its home position after releasing the first welding gun and before picking up the second welding gun. This condition interrupted the automatic welding sequence, increased production downtime, and reduced equipment availability. Initial corrective actions, such as controller reset and temporary cable reconnection, only restored robot operation for a short period before the alarm reappeared during subsequent production cycles.

Therefore, this study investigates the root causes of the TC_INNEST alarm by analyzing both external communication components and the internal condition of the robot controller. The findings are expected to provide an effective corrective maintenance strategy for improving robot reliability, reducing production downtime, and supporting more stable operation of multigun welding systems in automotive manufacturing.

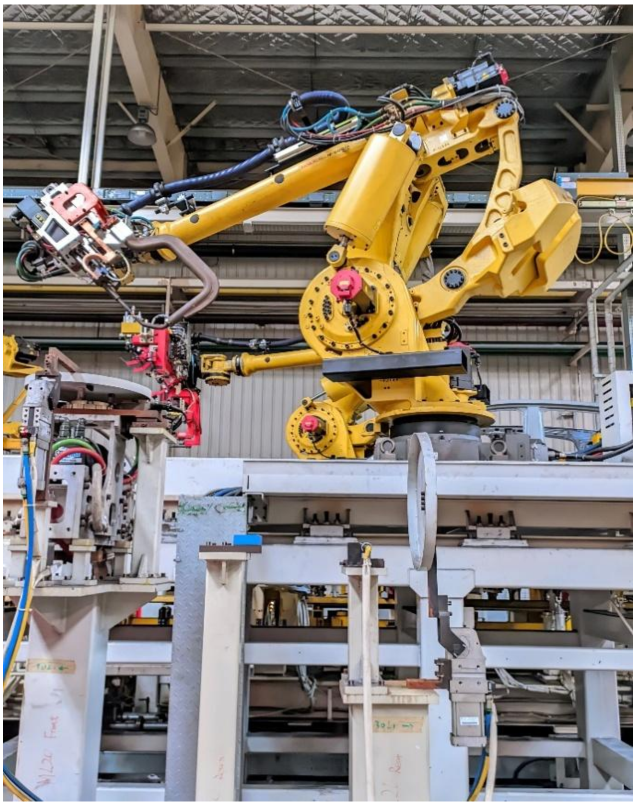

Fig. 1 Robot Fanuc M-900iA

I.II. Literature Review

Industrial robots have become an essential component of modern manufacturing systems because they provide high productivity, precision, and operational consistency. Smart manufacturing systems integrate robots, sensors, PLCs, IoT devices, and communication networks into highly interconnected production environments. As system complexity increases, failures occurring in communication or control components can propagate throughout the production process, making early fault diagnosis and effective maintenance strategies essential for maintaining production continuity [8]. As robot applications become increasingly complex, fault detection and diagnosis have become important research topics to improve system reliability and minimize unexpected production downtime [9]. Various studies have proposed intelligent fault diagnosis methods for industrial robots using data-driven approaches, machine learning, and artificial intelligence to identify abnormal operating conditions at an early stage [10]. Recent advances in intelligent fault diagnosis demonstrate that machine learning and deep learning techniques improve fault detection accuracy and support predictive maintenance in complex industrial systems [11].

In automotive manufacturing, resistance spot welding robots operate continuously under demanding production conditions, making equipment reliability a critical factor for maintaining production efficiency. Recent studies have developed fault diagnosis models specifically for body-in-white welding robots by integrating multiple decision-making algorithms to improve diagnostic accuracy [7]. In addition, hybrid artificial intelligence methods have demonstrated promising performance in diagnosing complex faults occurring in articulated industrial robots [12]. Data-driven fault diagnosis methods based on convolutional neural networks have demonstrated improved capability in identifying industrial robot faults through automatic feature extraction from monitoring data [13].

Reliable communication between the robot controller and peripheral devices is equally important for ensuring safe robot operation. Modern robotic systems employ industrial communication networks to exchange real-time control commands, sensor feedback, and interlock information during automated production processes. Real-time monitoring systems enable early detection of communication abnormalities before they develop into major equipment failures [14]. Furthermore, digital twin technology combined with deep learning has recently been introduced to improve industrial robot fault diagnosis through virtual system monitoring and predictive analysis [15].

Besides fault diagnosis, predictive maintenance has become one of the major research directions for improving industrial robot reliability. Digital twin technology enables continuous monitoring of industrial robots by synchronizing physical equipment with virtual models, allowing maintenance engineers to evaluate equipment conditions and predict future failures more effectively [16]. Predictive maintenance utilizes condition monitoring, operational data, and degradation analysis to identify potential failures before equipment breakdown occurs [17]. Several researchers have emphasized that reliability-centered maintenance strategies significantly reduce unplanned downtime while improving equipment availability in automotive robotic welding systems [2]. Predictive maintenance has evolved from traditional preventive maintenance by utilizing real-time operational data, digital models, and condition monitoring to predict equipment degradation before failures occur, thereby improving maintenance efficiency and reducing production downtime [18].

Although previous studies have extensively investigated intelligent fault diagnosis, predictive maintenance, and communication monitoring for industrial robots, most of them primarily focus on software-based diagnosis, data-driven algorithms, or external communication networks [19], [20], [21]. Comparatively fewer studies investigate how degradation of internal controller components, communication cables, and physical electrical connections contributes to recurring robot alarms under actual industrial operating conditions. This limitation provides an opportunity to further investigate practical maintenance issues encountered in automotive manufacturing environments.

I.III. Research Gap

Previous studies have extensively investigated fault diagnosis methods for industrial robots by employing artificial intelligence, machine learning, digital twin technology, and predictive maintenance approaches to improve fault detection accuracy and system reliability [9], [15], [17]. Artificial intelligence and machine learning have increasingly been integrated into robotic welding systems to improve welding quality, process monitoring, and production efficiency [22]. Other studies have also focused on communication monitoring, control system diagnosis, and reliability-centered maintenance to minimize production downtime in automated manufacturing environments

[2], [14], [4].

However, most existing studies primarily emphasize algorithm-based diagnosis, software monitoring, or external communication networks, while limited attention has been given to the influence of internal controller conditions, communication cable degradation, and electrical contact contamination on recurring robot alarms under actual production environments. Recent reviews also highlight that translating advanced fault-diagnosis methods into practical maintenance solutions for complex industrial robots remains a challenge, particularly when multiple hardware and communication components interact during operation.

Therefore, this study addresses this research gap by investigating the TC_INNEST alarm in a FANUC M-900iA multigun welding robot through a comprehensive analysis of both external communication components and the internal controller system under real industrial operating conditions. Unlike previous studies that mainly concentrate on intelligent diagnostic models, this research emphasizes engineering-based root cause analysis and corrective maintenance implementation to eliminate recurring alarms and improve production reliability.

I.IV. Research Objectives

This study aims to identify the root causes of the recurring TC_INNEST alarm, analyze the influence of communication components on alarm occurrence, evaluate the effectiveness of corrective maintenance actions, and propose practical maintenance recommendations to improve robot reliability.

II. Research Methodology

II.I. Research Design

This study employed a qualitative case study approach to investigate the recurring TC_INNEST alarm in a FANUC M-900iA multigun welding robot operating in an automotive manufacturing environment. The research was designed to identify the root causes of the alarm and evaluate the effectiveness of corrective maintenance actions under actual production conditions.

The investigation focused on analyzing the interaction between the robot controller, DeviceNet communication system, welding gun interface, communication cables, and internal controller components during the automatic gun-changing sequence. Direct field observations were conducted while the production line was in normal operation to understand the alarm characteristics and identify factors contributing to the recurring TC_INNEST alarm.

An engineering-oriented troubleshooting approach was adopted throughout the study. The research process included problem identification, field observation, technical inspection, implementation of corrective maintenance actions, and post-maintenance performance evaluation. The collected operational data were then analyzed to determine the effectiveness of the implemented maintenance strategy in eliminating the recurring TC_INNEST alarm and improving the operational reliability of the robotic welding system.

II.II. Experimental Setup

The study was conducted in the Body Shop production line of an automotive manufacturing company where a FANUC M-900iA multigun welding robot was used for resistance spot welding operations. The investigated robotic system consisted of a FANUC robot controller, a DeviceNet communication network, a dual welding gun configuration, communication cables, sola cables, and peripheral devices responsible for executing the automatic welding process.

During normal production, the robot automatically performed welding operations using two welding guns through a tool-changing mechanism. The TC_INNEST alarm was consistently observed during the transition from Gun 1 to Gun 2, particularly when the robot returned to the home position before engaging the second welding gun. This operating sequence became the primary focus of the investigation because it represented the condition under which the alarm repeatedly interrupted the production cycle.

To evaluate the root cause of the recurring alarm, the experimental investigation involved direct observation of robot operation, inspection of communication components, verification of DeviceNet connections, examination of controller conditions, and implementation of corrective maintenance actions. The effectiveness of each maintenance activity was evaluated based on the recurrence of the TC_INNEST alarm and the operational stability of the robotic welding system after maintenance.

Table 1. Alarm Experimental System Specifications

Parameter
Robot Model
Robot Application
Welding System
Robot Controller
Communication Network
Tool Changer
Welding Guns
Automotive Body Shop
Alarm Investigated
Maintenance Activities

II.III. Data Collection

Data were collected directly from the production line through field observation, technical inspection, alarm history analysis, and maintenance documentation. The data collection process focused on identifying the operational conditions associated with the recurring TC_INNEST alarm and evaluating the effectiveness of corrective maintenance actions implemented on the robotic welding system.

Field observations were conducted during normal production to monitor the automatic gun-changing sequence, particularly the transition from Gun 1 to Gun 2, where the TC_INNEST alarm occurred more than **10 times per production shift**, producing **1–3 minutes** of downtime per occurrence before corrective maintenance. Robot operational status, alarm messages displayed on the teach pendant, and production interruptions caused by the alarm were carefully recorded throughout the observation period.

Technical inspections were performed on the robot controller, DeviceNet communication network, communication cables, sola cables, connectors, and internal controller components to identify possible sources of communication failure or interlock disturbances. Maintenance documentation, including controller reset activities, cable replacement, controller cleaning, and component inspections, was also collected to support the engineering analysis and verify the effectiveness of each corrective maintenance action.

II.IV. Research Flowchart

The research methodology applied in this study is summarized in the form of a systematic flowchart to illustrate the sequence of activities performed during the investigation of the recurring TC_INNEST alarm. The flowchart presents the overall engineering process, starting from problem identification, data collection, technical inspection, implementation of corrective maintenance actions, and evaluation of the maintenance results. This structured approach ensures that each stage of the investigation is conducted systematically and enables effective identification of the root causes contributing to the recurring alarm in the robotic welding system.

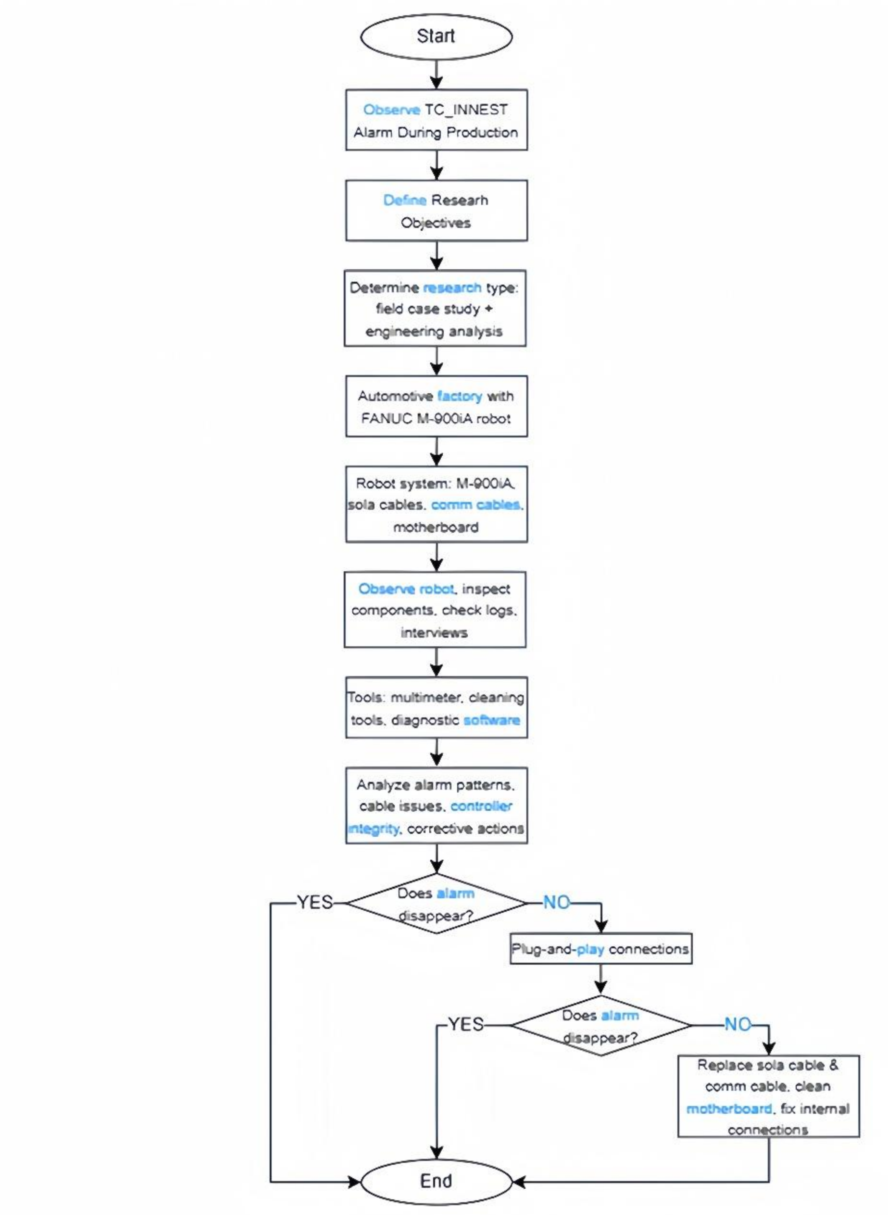

Fig. 2 Research Flowchart

II.V. Research Limitations

The scope and limitations of the proposed research methodology are described as follows. This study was conducted as a qualitative case study on a single FANUC M-900iA multigun welding robot operating in one automotive body shop production line. Therefore, the findings mainly represent the maintenance characteristics of the investigated production environment and may not be directly generalized to different robot models, controller architectures, or industrial communication systems. Future studies should investigate multiple robotic platforms and employ quantitative reliability analyses to validate the proposed maintenance strategy under broader industrial conditions.

III. Experimental Process and Data

This section describes the experimental procedures conducted during the investigation of the recurring **TC_INNEST** alarm on the FANUC M-900iA multigun welding robot and presents the operational data collected throughout the study. The experimental process was designed to identify the sequence of alarm occurrence, evaluate the condition of the communication and control systems, and assess the effectiveness of corrective maintenance actions under actual production conditions. The collected data serve as the basis for the analysis and discussion presented in the subsequent section.

III.I. Experimental Setup

Figure 3 illustrates the DeviceNet communication module responsible for data exchange between the FANUC robot controller and peripheral devices. Figure 4 presents the DeviceNet specification installed in the investigated robotic system. Figure 5 shows the dual welding gun stand utilized during the automatic gun-changing sequence, whereas Figure 6 illustrates the communication module mounted on the gun stand which transfers communication signals between the robot controller and the welding equipment during production.

Fig. 3 DeviceNet Module

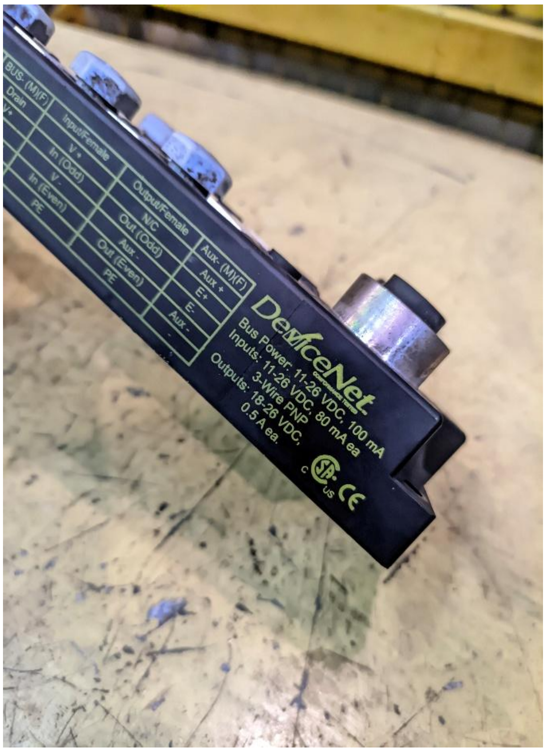

Fig. 4 DeviceNet Spec

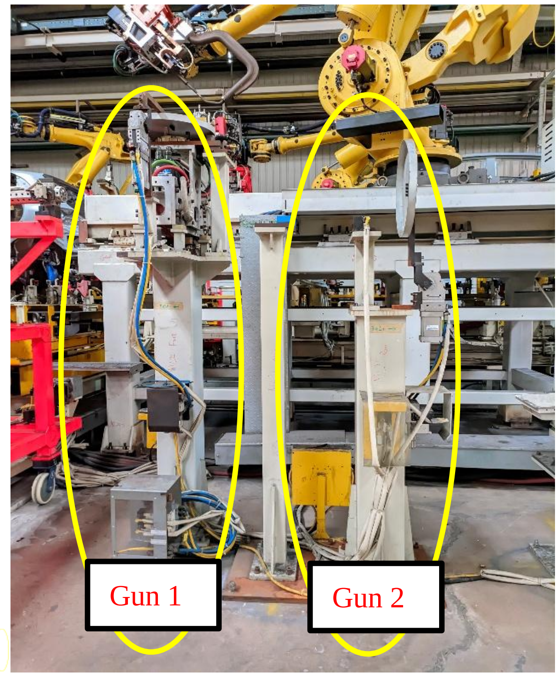

Fig. 5 Dual Welding Gun Stand

Fig. 6 DeviceNet Communication Module Installed on the Gun Stand

III.II. Experimental Process

The experimental investigation was conducted during normal production in an automotive Body Shop where the FANUC M-900iA multigun welding robot was continuously operated for resistance spot welding applications. The investigation focused on the automatic gun-changing sequence because the TC_INNEST alarm repeatedly occurred during the transition between Gun 1 and Gun 2.

During the investigation, the FANUC Teach Pendant was used as the primary interface to monitor robot operating status, alarm messages, and execution sequences during production. The displayed alarm history and operational information were recorded to identify the exact sequence leading to the recurring TC_INNEST alarm. No modification of the robot control program or welding algorithm was performed during this study. The robot continued operating with its original production program, while all maintenance activities focused exclusively on communication hardware inspection, controller diagnostics, cable replacement, and corrective maintenance. Therefore, this study evaluates the maintenance process under actual industrial operating conditions without altering the original robot control logic.

The experimental process began with direct observation of the robot operation to identify the sequence in which the alarm occurred. During each production cycle, robot movements, alarm messages displayed on the teach pendant, and production interruptions were carefully monitored and documented. Particular attention was given to the robot position immediately after releasing Gun 1 and before picking up Gun 2, where the recurring alarm was consistently detected.

Following the observation stage, technical inspections were carried out on the DeviceNet communication network, communication cables, sola cables, robot controller, and internal controller components. Several corrective maintenance actions, including controller reset, plug-and-play reconnection, cable replacement, controller cleaning, and replacement of internal communication cables, were implemented sequentially to evaluate their effectiveness in eliminating the recurring TC_INNEST alarm.

Finally, robot performance was evaluated after each corrective maintenance action by monitoring alarm recurrence, production downtime, and robot operational stability during subsequent production cycles.

III.III. Experimental Data

The experimental data were collected during the investigation of the recurring TC_INNEST alarm under actual production conditions. The data consisted of robot operational observations, alarm history records, technical inspection results, and maintenance documentation obtained throughout the troubleshooting process. These data were used to evaluate the operating condition of the robotic welding system before and after corrective maintenance activities.

During the observation period, the TC_INNEST alarm consistently appeared under identical operating conditions. The collected operational data indicate that the alarm occurred exclusively during the automatic gun-changing sequence, particularly between the release of Gun 1 and the engagement of Gun 2. These experimental observations provide the basis for the subsequent root cause analysis presented in Section 4.

Table 2. Alarm occurrence

Parameter	Observation
Alarm	TC_INNEST
Robot	FANUC M-900iA
Alarm Position	Home Position
Process	Gun 1 → Gun 2
Frequency	>10 alarms per shift
Downtime	1-3 min per alarm

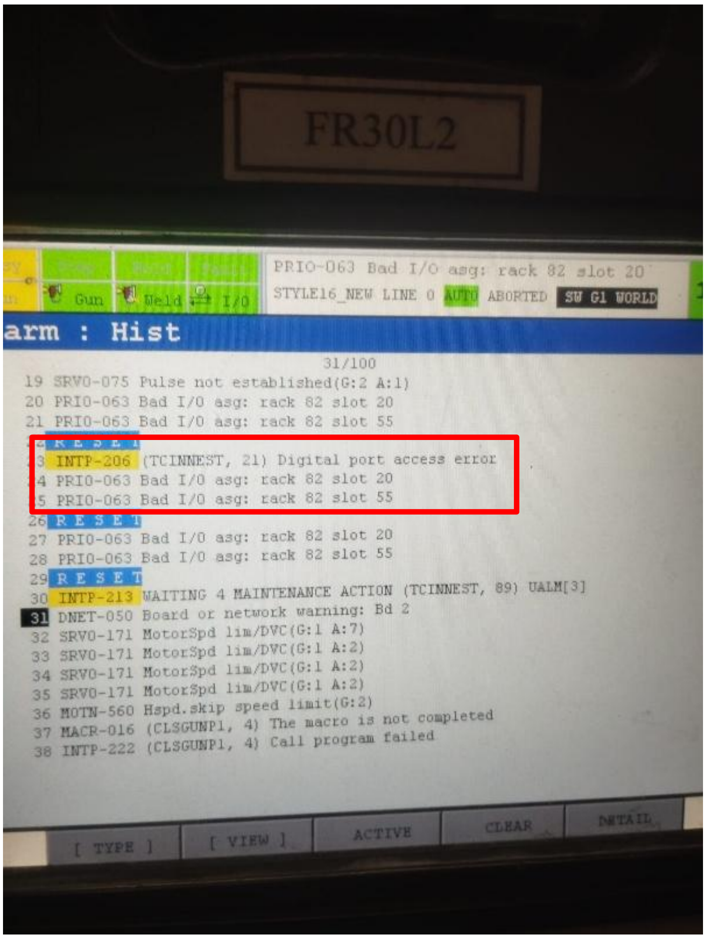

Fig. 7 Teach Pendant Display Showing the TC_INNEST Alarm

IV. Results and Discussion

The results presented in this section are based on field observations, technical inspections, and maintenance activities conducted during the investigation of the recurring TC_INNEST alarm in the FANUC M-900iA multigun welding robot. The findings are discussed to explain the alarm characteristics, identify the root causes, evaluate the effectiveness of corrective maintenance actions, and compare the obtained results with previous studies related to industrial robot fault diagnosis and maintenance.

IV.I. TC_INNEST Alarm Characteristics

The experimental results demonstrated that the TC_INNEST alarm consistently occurred during the automatic gun-changing sequence of the FANUC M-900iA multigun welding robot. As presented in Table 2, the alarm repeatedly appeared when the robot returned to the home position after releasing Gun 1 and before engaging Gun 2. Each alarm interrupted the welding cycle and required maintenance intervention before production could resume.

The recorded operational data showed that the alarm occurred more than 10 times per production shift, resulting in approximately 1–3 minutes of downtime for each occurrence. These repeated interruptions reduced equipment availability and negatively affected production continuity. No similar alarm was observed during continuous welding operations using a single welding gun, indicating that the problem was closely associated with the automatic tool-changing sequence.

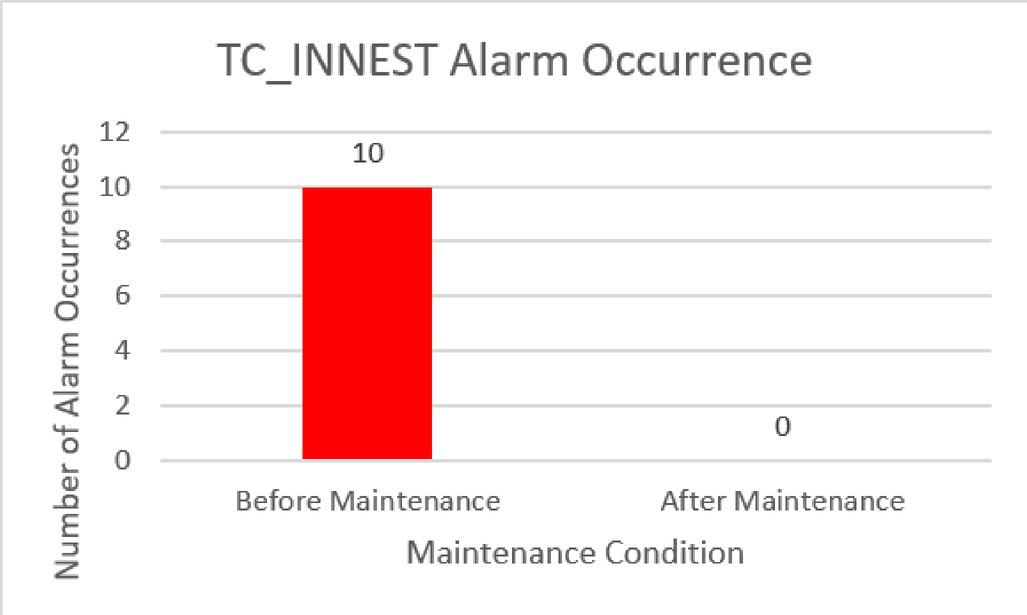

Fig. 8 Comparison of TC_INNEST alarm occurrence before and after comprehensive corrective maintenance.

Table 3. Performance Improvement After Maintenance

Indicator	Before	After
Alarm Frequency	>10/shift	0
Downtime	1–3 min	0
Robot Stability	Frequently interrupted	Stable
Production Continuity	Interrupted	Continuous

Figure 8 demonstrates that the implemented corrective maintenance significantly reduced the occurrence of the TC_INNEST alarm. Prior to maintenance, the alarm occurred more than ten times per production shift, whereas no recurrence was observed after communication cable replacement, controller cleaning, and restoration of the communication system. These findings confirm the effectiveness of the proposed maintenance strategy in improving robot reliability and production continuity.

The observed alarm characteristics suggest that communication and interlock verification play a critical role during the gun-changing process. Similar findings have been reported in previous studies, which identified communication failures and control system abnormalities as major causes of unexpected interruptions in industrial robotic welding systems [7], [14], [4]. Furthermore, condition monitoring and reliability-centered maintenance are essential for minimizing production downtime and improving the operational reliability of industrial robots [9], [2].

IV.II. Root Cause Analysis

To identify the root cause of the recurring TC_INNEST alarm, comprehensive inspections were conducted on the robot controller, DeviceNet communication system, communication cables, and internal controller components, as presented in Figures 9–11.

Fig. 9 FANUC Robot Controller

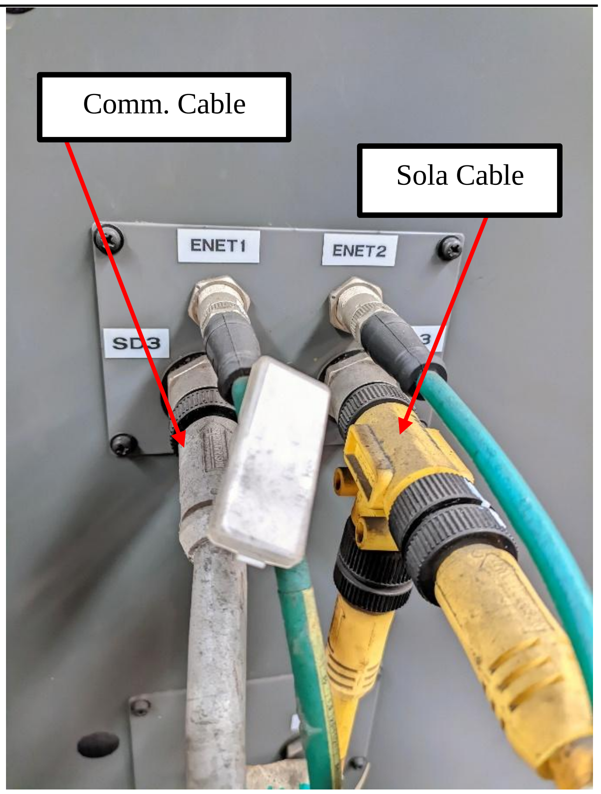

Fig. 10 Power Supply (SOLA) Cable and Communication Cable

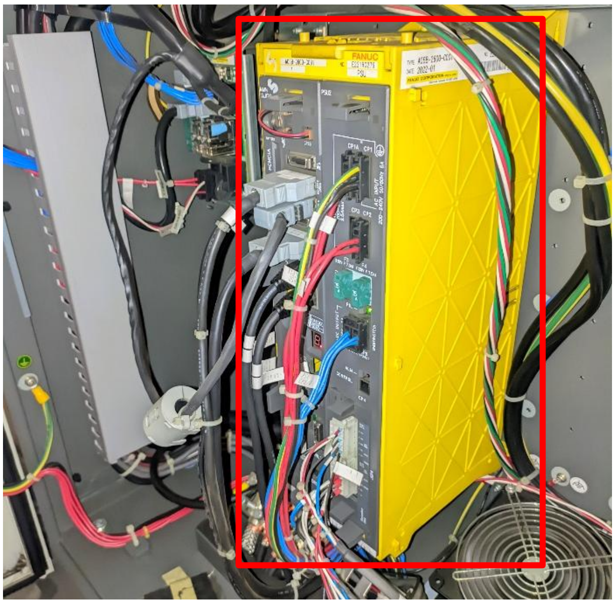

Fig. 11 Internal Controller Motherboard of the FANUC Robot Controller

The root cause investigation revealed that the recurring TC_INNEST alarm was caused by the combined degradation of communication-related components rather than a single component failure. Technical inspections of the robot controller, DeviceNet communication system, communication and sola cables, and internal controller motherboard (Figures 9–11) identified connector oxidation, dust contamination, deteriorated communication cables, and unstable internal communication connections, which reduced communication stability during the automatic gun-changing sequence and prevented successful interlock verification between the robot controller and peripheral devices. These findings are consistent with previous studies emphasizing the importance of communication reliability and predictive maintenance in industrial robotic welding systems [7], [14], [4], [9], [17], [3].

After controller cleaning, replacement of degraded communication cables, and restoration of DeviceNet communication, the TC_INNEST alarm no longer recurred during subsequent production cycles, confirming the effectiveness of the proposed maintenance strategy for improving robot reliability and production continuity [15], [12], [19].

IV.III. Evaluation of Corrective Maintenance

The effectiveness of the implemented corrective maintenance strategy was evaluated by monitoring the recurrence of the TC_INNEST alarm and the operational performance of the robotic welding system after each maintenance activity. Initial corrective actions, including controller reset and temporary plug-and-play reconnection, successfully restored robot operation but provided only temporary recovery, as the TC_INNEST alarm reappeared during subsequent production cycles.

Comprehensive corrective maintenance was then performed by replacing degraded communication cables, sola cables, and DeviceNet components, followed by controller motherboard cleaning and replacement of internal communication cables. After these maintenance activities, no recurrence of the TC_INNEST alarm was observed during normal production. The maintenance strategy reduced the alarm occurrence from more than ten events per production shift to zero, corresponding to a 100% reduction in alarm frequency, while eliminating production downtime associated with the alarm and restoring stable automatic gun-changing operation.

These results demonstrate that maintaining the integrity of both external communication components and internal controller hardware is essential for ensuring reliable operation of multigun robotic welding systems. The findings are consistent with previous studies showing that reliability-centered maintenance, predictive maintenance, and continuous monitoring of industrial communication systems significantly improve equipment availability, operational reliability, and reduce unplanned downtime [2], [17], [3], [9], [23], [24].

Table 4. Chronological Troubleshooting Actions and Results of the TC_INNEST Alarm

Performance Indicator	Before Maintenance	After Maintenance
TC_INNEST Alarm	>10 occurrences/shift	No recurrence
Downtime	1–3 min/alarm	0 min
Robot Stability	Frequently interrupted	Stable
Gun-Changing Operation	Unsuccessful	Successful
Production Continuity	Interrupted	Continuous

IV.III. Discussion

The findings of this study demonstrate that recurring TC_INNEST alarms in the FANUC M-900iA multigun welding robot were primarily associated with communication instability and degradation of both external and internal hardware components. Unlike studies that mainly emphasize intelligent fault diagnosis algorithms and data-driven monitoring techniques [9], [15], [12], this research highlights that physical deterioration of communication cables, DeviceNet components, controller motherboard contamination, and internal communication connections can significantly affect robot operation under actual production conditions.

Previous studies have reported that communication failures, control system abnormalities, and insufficient maintenance strategies may reduce the operational reliability of industrial robotic systems [7], [2], [4]. The present study supports these findings by demonstrating that communication-related failures directly contributed to repeated interruptions during the automatic gun-changing sequence. However, this research extends previous work by providing evidence from a real industrial environment, showing that recurring alarms may result from the interaction of multiple hardware components rather than from a single communication failure.

Furthermore, recent advances in predictive maintenance, condition monitoring, and intelligent fault diagnosis have improved the capability to detect equipment degradation before catastrophic failure occurs [17], [19], [24]. Nevertheless, the present investigation indicates that routine physical inspection and maintenance of communication components remain essential, particularly for robotic welding systems operating under continuous production conditions. Therefore, combining predictive maintenance technologies with systematic engineering inspection may provide a more comprehensive maintenance strategy for improving robot reliability.

From an industrial perspective, the implementation of comprehensive corrective maintenance not only eliminated the recurring TC_INNEST alarm but also improved production continuity by reducing unplanned downtime and increasing equipment availability. These findings provide practical guidance for maintenance engineers in diagnosing similar communication-related alarms and support the implementation of more effective preventive maintenance programs in automotive manufacturing environments.

Unlike previous studies focusing mainly on algorithm-based diagnosis, this study demonstrates that comprehensive inspection of both internal controller components and external communication hardware provides a practical and effective strategy for eliminating recurring TC_INNEST alarms in industrial multigun welding robots. Data fusion techniques combine multiple sources of monitoring information to improve fault diagnosis accuracy and support more reliable maintenance decision-making [6].

V. Conclusions and Recommendations

V.I. Conclusions

This study investigated the recurring TC_INNEST alarm in a FANUC M-900iA multigun welding robot operating in an automotive manufacturing environment. Field observations, technical inspections, and engineering analysis confirmed that the alarm was caused by communication instability resulting from the combined degradation of DeviceNet components, communication cables, sola cables, internal communication cables, and contamination of the controller motherboard.

The results demonstrate that temporary corrective actions, such as controller reset and plug-and-play reconnection, restored robot operation only temporarily and failed to eliminate the root cause. In contrast, comprehensive corrective maintenance involving communication cable replacement, controller cleaning, restoration of DeviceNet communication, and replacement of internal communication cables successfully eliminated the recurring TC_INNEST alarm and improved robot operational stability.

Compared with previous maintenance practices, the proposed maintenance strategy adopts a comprehensive engineering inspection of both external communication devices and internal controller components, enabling accurate root cause identification and permanent elimination of the recurring alarm. Therefore, the proposed approach provides a more reliable and sustainable maintenance strategy for improving robotic welding system reliability, minimizing production downtime, and supporting production continuity in automotive manufacturing environments.

V.II. Recommendations

Based on the findings of this study, routine preventive maintenance focusing on the DeviceNet communication system, communication cables, connectors, and internal controller components is recommended to prevent recurring communication-related alarms and improve robot reliability. Periodic inspection and cleaning of robot controller components should also be incorporated into maintenance schedules to maintain communication stability and reduce unexpected production interruptions. Future studies are encouraged to integrate real-time condition monitoring, predictive maintenance, and artificial intelligence-based diagnostic techniques, as well as to evaluate similar communication-related alarms in different industrial robot models and manufacturing environments to validate the applicability of the proposed maintenance strategy.

References

[1] N. Gündoğan, "Technological expectations and challenges of industrial welding robots," *EJONS Int. J.*, 2024.
[2] H. T. O. Alaka, K. Mpofu, B. I. Ramatsetse, T. A. Adegbola, and M. O. Adeoti, "Reliability-centered maintenance in automotive robotic welding machines," *Front. Robot. AI*, 2025.
[3] R. K. Mobley, *An Introduction to Predictive Maintenance*. Elsevier, 2020.
[4] S. Ji and Z. Li, "Control system errors in industrial welding robots," in *International Conference on Mechanical Engineering and Automation*, 2025.
[5] P. Kumar, S. Khalid, and H. S. Kim, "Prognostics and Health Management of Rotating Machinery of Industrial Robot with Deep Learning Applications: A Review," *Mathematics*, vol. 11, 2023, doi: 10.3390/math11133008.
[6] A. E. Chaleshtori and A. Aghaie, "Data Fusion Techniques for Fault Diagnosis of Industrial Machines: A Survey," 2022.
[7] B.-C. Zhang, J.-D. Wang, Z. Zheng, D.-X. Chen, and X.-J. Yin, "Fault diagnosis for body-in-white welding robot based on multi-layer belief rule base," *Appl. Sci.*, 2023.
[8] J. Aldrini, I. Chihi, and L. Sidhom, "Fault Diagnosis and Self-Healing for Smart Manufacturing: A Review," *J. Intell. Manuf.*, vol. 35, pp. 2441–2473, 2024, doi: 10.1007/s10845-023-02165-6.
[9] Y. Lei, Z. Liu, H. Wang, N. Li, and Y. Qiao, "Condition monitoring and fault diagnosis of industrial robots: A review," *Sci. China Technol. Sci.*, 2025.
[10] A. H. Sabry and U. A. B. Ungkulddin, "A review on fault detection and diagnosis of industrial robots and multi-axis machines," *Results Eng.*, 2024.
[11] S. Qiu *et al.*, "Deep Learning Techniques in Intelligent Fault Diagnosis and Prognosis for Industrial Systems: A Review," *Sensors*, vol. 23, 2023, doi: 10.3390/s23031305.

[12] Y. Zhang, Z. Li, and X. Chen, "Hybrid AI-based fault diagnosis for articulated industrial robots," *J. Intell. Manuf.*, 2024.

[13] Y. Liu, C. Chen, T. Wang, and L. Cheng, "An Attention Enhanced Dilated CNN Approach for Cross-Axis Industrial Robotics Fault Diagnosis," *Auton. Intell. Syst.*, vol. 2, 2022, doi: 10.1007/s43684-022-00030-6.

[14] M. Tan, P. Wang, and W. Luo, "Real-time monitoring and fault diagnosis system for industrial robots," in *IEEE Conference on Industrial Cyber-Physical Systems*, 2024.

[15] I. Ben Hnaien, E. Gascard, Z. Simeu-Abazi, and H. Dhouibi, "Fault diagnosis of industrial robots using digital twin and deep learning," in *Proceedings of the International Conference on Informatics in Control, Automation and Robotics*, 2025.

[16] P. Aivaliotis, Z. Arkouli, K. Georgoulias, and S. Makris, "Methodology for Enabling Dynamic Digital Twins and Virtual Model Evolution in Industrial Robotics: A Predictive Maintenance Application," *Int. J. Comput. Integr. Manuf.*, vol. 36, no. 7, pp. 947–965, 2023, doi: 10.1080/0951192X.2022.2162591.

[17] T. Wang, H. Liu, and Y. Xu, "Predictive maintenance for industrial robot drive systems using deep learning," *Sensors*, 2025.

[18] D. Zhong, Z. Xia, Y. Zhu, and J. Duan, "Overview of Predictive Maintenance Based on Digital Twin Technology," *Heliyon*, vol. 9, 2023, doi: 10.1016/j.heliyon.2023.e14534.

[19] G. Vachtsevanos, F. Lewis, and M. Roemer, *Intelligent Fault Diagnosis and Prognosis for Engineering Systems*. Wiley, 2020.

[20] C. Li, D. He, and S. Wang, "Deep scattering spectrum for fault diagnosis in industrial systems," *Mech. Syst. Signal Process.*, 2022.

[21] J. Park, S. Lee, and Y. Kim, "Fault diagnosis of wafer handling robots using hybrid modeling," *IEEE Trans. Semicond. Manuf.*, 2024.

[22] D. Bassir, "Integration of the AI and ML Approaches for Prediction Analysis in Welding: Review," 2023.

[23] R. Teti, K. Jemielniak, G. O'Donnell, and D. Dornfeld, "Advanced monitoring of machining operations," *CIRP Ann.*, 2020.

[24] A. K. S. Jardine, D. Lin, and D. Banjevic, "A review on machinery diagnostics and prognostics," *Mech. Syst. Signal Process.*, 2021.