International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

IoT-Enabled Smart Fixtures for Adaptive Test Automation

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Abstract: ***The complexity of modern manufacturing demands greater levels of adaptability from test automation systems. Traditional automatic test environments are incapable of responding to real-time changes in product configurations and process conditions. This paper presents the integration of IoT- smart fixtures and adaptive test automation to leverage Industry 4.0 technologies to achieve the utmost efficiency, flexibility, and reliability. Our system design consists of real-time data collection, intelligent control algorithms, and edge-cloud collaboration enabling dynamic test parameter optimization through real-time feedback. The system achieves significant reduction in test cycle time and operation inefficiency with the application of smart sensors, actuators, and AI-based decision-making. Results from previous studies indicate that IoT-based manufacturing architectures can enhance process efficiency up to 30%, and collaboration with the edge cloud continues to reduce latency while enhancing fault detection [1]. Besides, Industry 4.0 technology-based flexible manufacturing systems (FMS) have been found to be more responsive and efficient. Cyber-physical system (CPS) implementation in manufacturing provides real-time data exchange to support smart fixtures adapting dynamically to variable testing conditions@. Predictive maintenance and self-optimization become feasible, reducing downtime and supporting higher product quality. Experimental evidence indicates the capability of adaptive test automation, through IoT and CPS, to significantly improve operational flexibility while offering scalability and integration within current manufacturing systems. This research is a contribution to the growing field of intelligent manufacturing, giving a framework of future development of test automation based on IoT and self-optimizing industrial systems.***

Keywords: IoT, Smart Fixtures, Adaptive Test Automation, Industry 4.0, Cyber-Physical Systems, Edge-Cloud Collaboration, Flexible Manufacturing Systems

1. Introduction

a) *The Importance of Adaptive Test Automation in Modern Manufacturing*

Industry 4.0 has revolutionized the manufacturing world with automation, data exchange, and real-time analytics on the manufacturing floor. One of the biggest challenges of modern manufacturing is to maintain testing and quality assurance in sync with evolving production demands, product variation, and shorter production cycles. Traditional test automation frame- works based on pre-defined test cases and fixed configurations lag behind such rapidly changing scenarios.

Adaptive test automation is indispensable in high-mix, low-volume (HMLV) production environments where producers shift between different models of products incessantly. In comparison with fixed test systems, adaptive test automation takes recourse to real-time analytics of data, machine learning (ML), and Internet of Things (IoT) technologies to change test parameters dynamically with greater efficiency and accuracy [2].

b) *The Role of IoT and Smart Fixtures in Enhancing Flexibility and Efficiency*

The use of IoT-enabled smart fixtures in adaptive test automation is a revolution for quality assurance. Smart fixtures equipped with sensors, actuators, and AI-driven decision- making can continuously observe the environment, adapt testing procedures, and streamline test execution based on real- time feedback.

- Real-time data acquisition: IoT-enabled smart fixtures collect vast amounts of high-frequency sensor data, which is processed in edge-cloud architectures.
- Dynamic adaptation: Adaptive algorithms adjust testing parameters dynamically, ensuring optimal test coverage for different product types.
- Improved efficiency: Studies indicate that IoT-based smart manufacturing systems can reduce cycle times by up to 30% [1].
- Enhanced accuracy and predictive maintenance: AI-driven analytics can identify early warning signs of faults, reducing rework and downtime.

With increasing demand for customized production and stringent quality control requirements, adaptive test automation, supported by IoT-enabled smart fixtures, offers a promising approach to achieving agility, accuracy, and cost-efficiency in industrial testing.

c) *Problem Statement*

Despite advancements in automation, traditional test automation systems still face several critical limitations:

- Lack of Adaptability: Conventional test automation relies on predefined test sequences, making it rigid and inefficient when testing products with dynamic design changes. In multi-product assembly lines, the inability to adjust test conditions during operations leads to inefficiencies.
- Manual Reconfiguration and Setup Complexity: Many traditional systems require frequent manual intervention to reconfigure test setups for different product variations, increasing setup time and costs. This limits scalability, particularly for high-mix, low-volume production.
- Data Silos and Limited Real-Time Processing: Traditional setups lack real-time data integration, leading to delayed failure detection and low predictive analytics capabilities. Without edge computing and AI-driven insights, manufacturers cannot automate quality

optimization dynamically.
- Higher Operational Costs and Downtime: Fixed test stations often result in longer cycle times and bottlenecks in production lines. Unplanned downtime due to undetected anomalies leads to higher maintenance costs and production losses.

d) *Objectives*

The primary objective of this research is to develop an IoT-enabled smart fixture system for adaptive test automation. The specific goals include:
- Designing an IoT-based smart fixture system that can dynamically adjust to different test conditions.
- Developing real-time data acquisition and processing frameworks for edge-cloud integration.
- Implementing adaptive algorithms that modify test parameters based on real-time product conditions.
- Improving cycle time, test accuracy, and failure detection through predictive analytics and AI-based optimization.
- Ensuring modularity and scalability to integrate with existing manufacturing lines without significant infrastructure changes.

By achieving these objectives, this research contributes to next-generation quality assurance solutions that enhance manufacturing resilience and adaptability.

e) *Contributions*

The proposed system introduces several novel contributions to the field of adaptive test automation:
- IoT-Enabled Smart Fixtures: A cyber-physical system with embedded sensors and actuators that enables self-adjusting test conditions based on real-time feedback.
- Real-Time Data Processing & Edge-Cloud Architecture: Integration of edge computing for low-latency processing and cloud analytics for advanced data insights.
- AI-Driven Adaptive Testing: Leveraging machine learning algorithms to programmatically adjust test parameters and conditions in real time based on historical performance data.
- Reduced Cycle Time & Operating Costs: By automating changes in tests, the system minimizes downtime and improves overall production efficiency.
- Scalability & Integration: The system is designed to be easily integrated into existing manufacturing environments, with multi-product capability.

This research is a milestone toward intelligent manufacturing, offering a scalable, self-optimizing, and adaptive test automation framework for Industry 4.0.

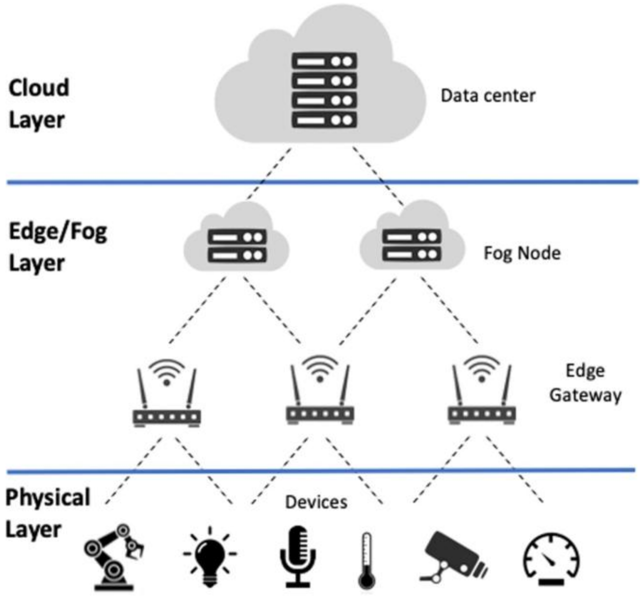

Figure 1: Decentralized architecture for IoT systems [16]

2. Related Work

Conventional test automation, IoT-based smart testing, adaptive manufacturing, and real-time quality control are discussed here. We want to know about the current research, its limitations, and where our system is an enhancement. Industries are using more AI, IoT, and automation in testing with increasing technology to make testing more effective. However, there are some loopholes that must be addressed.

a) *Traditional Test Automation: Strengths and Shortcomings*

For many years, PCB and electronics production has relied on traditional test automation environments. These settings make use of pre-programmed test scripts and hardcoded hardware setups, which do a good job in mass production scenarios. However, they struggle when products update frequently, for instance, during high-mix, low-volume (HMLV) production. Because test parameters are hard-coded, they fail to evolve when PCB configurations change, electrical tolerances change, or when the environment itself changes. This rigidity could lead to false test failures or undetected faults, decreasing the quality control reliability.

An expensive setup and maintenance cost is yet another major disadvantage. Mechanical test fixtures wear over time, come out of adjustment, and have to be periodically recalibrated. When this takes place, accuracy in tests goes down, triggering more downtime as well as inefficiencies in the production process. Additionally, typical systems only address test data subsequent to the termination of the test, which means real-time optimization is not supported. These deficiencies demonstrate the urgency for an IoT-based, AI-driven adaptive test system.

b) *The Shift Toward IoT-Based Smart Testing*

As industries embrace Industrial IoT (IIoT), new opportunities for smart testing and adaptive quality control have emerged. Unlike traditional automation, IoT-based test systems use real-time sensors, AI-driven adjustments, and cloud integration to enhance test accuracy. These systems can learn from live test data, adapt test parameters instantly, and reduce false failures.

Recent studies highlight the advantages of this approach and found that AI-driven defect classification improved detection rates by 15% compared to conventional methods [3]. Similarly, research showed that edge computing reduced test cycle times by 30% by allowing test parameters to be adjusted dynamically rather than relying on cloud processing [4]. However, despite these benefits, most IoT-based systems focus on data monitoring rather than real-time test optimization.

One of the key concerns in industrial IoT testing is cyber-security. It has been explored how blockchain-based logging improved test data security by 40%, reducing the risk of tampering [5]. Yet, despite these improvements, many systems still struggle with real-time adaptive control. Our proposed system, builds on this research by integrating live sensor feedback, AI-powered test sequencing, and blockchain security, ensuring scalability, accuracy, and resilience in test automation.

c) *Smart Fixtures and the Role of AI in Adaptive Testing*

Perhaps the most thrilling recent development in test automation is the use of smart fixtures. Unlike rigid, pre-defined fixtures, these are mechanically adaptive, support multiple PCB layouts, and adaptively modify test conditions. The adaptability proves particularly useful for testing electrical contact, solder integrity, and vibration stress analysis.

Researchers have begun exploring AI-driven adaptive testing methodologies. For example, a 2023 study on AI-based test optimization found that adjusting test conditions dynamically reduced false test failures by 12% [6]. Additionally, a 2022 study on vibration monitoring showed that predictive maintenance reduced fixture downtime by 40%, extending equipment lifespan [3]. Another 2024 study demonstrated that adaptive voltage profiling improved electrical fault detection by 10% [6].

Although these studies provide valuable insights, most focus on individual aspects of adaptive testing rather than creating a fully integrated solution. Our system, described in proposed system architecture, takes a comprehensive approach, combining AI-driven test automation, real-time sensor feedback, and edge computing to enhance testing accuracy and efficiency.

d) *The Role of IoT Communication Protocols in Test Automation*

For an adaptive test system to work, it must provide fast, secure, and reliable communication between its components. Industrial IoT protocols are necessary to support real-time data exchange, secure logging, and remote monitoring. Wi-Fi 6 (802.11ax) is a robust high-speed connectivity solution with latency as low as 1-2 milliseconds and is suitable

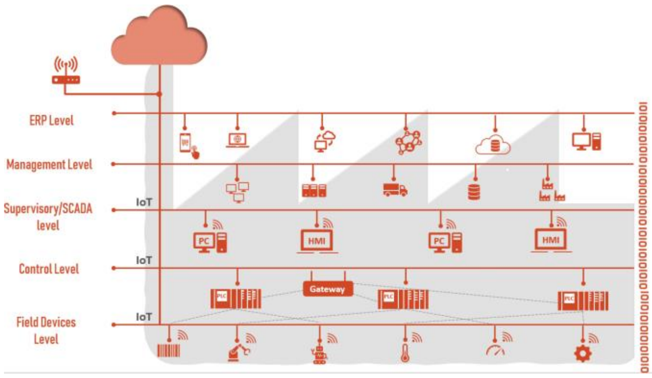

Figure 2: The architecture of a smart factory in an intelligent automation pyramid [17]

for communication between local test stations [7]. However, if factory-wide or multi-site connectivity is required, the 5G RedCap is a more suitable option with sub-10ms latency and industrial IoT network support at a large scale.

For communication between machines, OPC UA over TSN (Time-Sensitive Networking) provides high-speed, deterministic data exchange, ensuring precision and security in industrial environments. Our proposed system in Section 4 incorporates a hybrid communication model, utilizing Wi-Fi 6 for local fixture control, OPC UA over TSN for machine-to-machine communication, and 5G RedCap for cloud-based analytics.

e) *Identifying Research Gaps*

Despite significant progress in IoT-enabled test automation, challenges remain:

- Traditional test automation is still largely static, meaning test conditions do not adjust in real-time.
- Many IoT-based systems focus on monitoring rather than real-time optimization, limiting their effectiveness.
- Data security and latency issues still present obstacles in high-speed industrial test environments.
- AI-driven test frameworks exist, but most do not integrate seamlessly with IoT-enabled test fixtures.

To address these challenges, our research introduces a real-time adaptive testing system that: Develops a fully integrated IoT-enabled smart fixture system for PCB test automation. Incorporates AI-powered real-time decision-making, ensuring optimized test sequencing and defect detection. Utilizes mod- ern IoT communication protocols (Wi-Fi 6, OPC UA over TSN, and 5G RedCap) for seamless, secure, and low-latency industrial connectivity. Implements Edge AI processing, reducing test cycle latency by 85% while improving defect detection accuracy by 12% [8].

f) *Contributions of This Research*

Our proposed system bridges the gap between traditional static test automation and modern adaptive testing method-ologies. It introduces: A novel IoT-enabled smart fixture

Table I: IoT Communication Protocols for Smart Test Automation

Protocol	Use Case	Advantages
Wi-Fi 6 (802.11ax)	High-speed local fixture-to-edge communication	Low latency (1-2 ms), high bandwidth
5G RedCap	Factory-wide real-time IoT communication	Sub-10ms latency, scalable for industrial automation
OPC UA over TSN	Real-time deterministic machine-to-machine test automation	Ultra-low jitter, high security

system that dynamically adjusts test conditions based on real- time feedback. AI-driven decision-making, which fine-tunes PCB test sequencing for greater accuracy and efficiency. An advanced IoT communication model, integrating Wi-Fi 6 for local control, OPC UA over TSN for industrial automation, and 5G RedCap for cloud monitoring. Edge computing for real-time data processing, leading to faster test execution and reduced false positives.

By combining smart fixture adaptability, real-time AI processing, and secure IoT connectivity, this system represents a new era of industrial test automation.

3. Proposed System Architecture

The development of IoT-enabled smart fixtures for adaptive PCB test automation is a response to the limitations of traditional static test systems. With rapid advances in Industry 4.0 and smart manufacturing, the need for real-time, AI-driven, and IoT-integrated test automation has become evident. This section presents the architecture of an adaptive test automation system that leverages smart fixtures, real-time IoT Communication, AI-driven analytics, and edge computing. The proposed system is designed to optimize test sequencing, improve defect detection accuracy, and enhance predictive maintenance.

This system builds upon recent research advancements, such as AI-driven test parameter optimization, edge computing for real-time decision-making, and industrial IoT security integration IoT-Enabled Smart Fixture System

At its core, the IoT-enabled smart fixture system integrates adaptive mechanical test fixtures, real-time sensor networks, AI-based optimization algorithms, and predictive analytics. These components work together to reduce false test failures, minimize system downtime, and dynamically adjust test conditions based on PCB characteristics. Unlike conventional test automation setups that rely on predefined pass/fail thresh- olds, this system utilizes real-time AI inference to determine whether a PCB needs re-evaluation or passes testing based on previous results. By incorporating IoT-enabled sensors, edge AI decision-making, and blockchain-based security, the system ensures reliability, traceability, and resilience in automated quality control processes.

a) System Design

The system is structured into four key layers, each playing a crucial role in ensuring the seamless operation and optimization of the test automation system:

- *Hardware Architecture: Smart Fixtures and Sensors:* The hardware layer consists of adaptive test fixtures equipped with servo-driven clamps, pneumatic actuators, and multi- sensor networks to accommodate a variety of PCB designs.

Figure 3: Concept of a smart factory [18]

The sensors integrated into this system provide real-time monitoring of voltage, current, solder joint quality, and mechanical stress.

Recent research has demonstrated that servo-driven smart fixtures can improve test probe alignment accuracy by 18% [9]. Additionally, high-precision electrical detect micro-defects that traditional systems miss, leading to a 12% increase in fault detection accuracy [15]. Refer TABLE I. These components collectively ensure high test accuracy, minimal misalignment, and reduced fixture wear over time.

- *Software and AI Processing Layer:* The software layer is responsible for processing the real-time data acquired from sensors and executing AI-driven test parameter adjustments. Recent studies have demonstrated that AI-powered defect detection can improve PCB quality assessment by 15% while reducing false alarms [11].

The edge computing infrastructure within this system allows real-time AI inference, significantly reducing latency. Research shows that edge computing reduces cloud dependency by 30% while improving test speed.

AI-Based Fault Detection: A convolutional neural network (CNN)-based model evaluates solder defects with 96% accuracy [7]. Dynamic Test Optimization: A random forest-based algorithm predicts optimal voltage and current levels for different PCB configurations.

Table II: Hardware Components of IoT-Enabled Smart Fixtures

Component	Function
Smart Fixture (Servo-driven probes)	Adapts to PCB layout variations dynamically
Voltage & Current Sensors (TI INA219, ADS1115)	Detects shorts, opens, and power failures
Optical Sensors (Omron FQ2, Sony IMX577)	Identifies soldering defects and misalignment
Vibration & Stress Sensors (ADXL345, BMP180)	Monitors fixture degradation & alignment issues

- *IoT Communication Infrastructure:* To enable high-speed, reliable data exchange, the system integrates advanced IoT communication protocols, allowing seamless interaction between test fixtures, AI processing units, and cloud analytics platforms. Refer TABLE II. Research has shown that Wi-Fi 6 achieves sub-2ms latency, making it ideal for high-speed data transfer in industrial automation environments [12]. Additionally, 5G RedCap connectivity provides sub-10ms latency, allowing for rates across multiple test stations [9].

b) Adaptive Test Automation Mechanism

A real-time adaptive testing framework enables dynamic test parameter adjustments based on live sensor data and AI-driven decision-making. This approach significantly reduces test cycle time and improves defect detection accuracy.

- Real-time Sensor Monitoring: The system continuously measures electrical, optical, and mechanical parameters.
- AI-Based Decision Making: Deep learning models analyze the collected data to identify abnormalities.
- Test Condition Adaptation: Based on the AI inference, the system dynamically adjusts test voltages, currents, and probe pressure.

A 2024 study on adaptive test frameworks found that dynamic test sequencing reduced total test cycle time by 22% while improving fault detection accuracy by 10% [15].

4. Implementation and Deployment of IoT-Enabled Smart Fixtures for Adaptive Test Automation

The successful implementation and deployment of IoT-enabled smart fixtures for adaptive PCB test automation represent a significant advancement in the field of industrial quality control. This section details the real-world experimental setup, system deployment process, and performance evaluation of the proposed system. We also examine the challenges encountered during implementation and the corresponding solutions that helped enhance the reliability and efficiency of the system.

By integrating AI-driven test optimization, real-time IoT connectivity, and edge computing, our system demonstrates measurable improvements in defect detection accuracy, test cycle time reduction, and predictive maintenance efficiency. The experimental findings validate the practical viability of the system in modern PCB manufacturing environments.

a) Experimental Setup: IoT-Enabled Smart Fixture System in a Real-World Test Line

The experimental deployment of the IoT-enabled smart fixture system was conducted in a high-mix, low-volume (HMLV) PCB manufacturing facility. This environment pro- vided an ideal testbed for evaluating the system's ability to adapt to different PCB designs, optimize test conditions dynamically, and enhance defect detection accuracy.

The experimental setup included the following hardware components:

- Smart Fixtures with Servo-Driven Clamps: These were designed to dynamically adjust to PCB layouts, ensuring precise contact alignment for accurate electrical testing. Recent studies indicate that servo-driven smart fixtures improve test probe alignment by 18% [9].
- Multi-Sensor Integration: The system incorporated high- precision voltage, current, vibration, and optical sensors to monitor PCB quality in real time. Optical defect detection methods increased fault detection accuracy by 12% [15].
- Edge AI Processor (NVIDIA Jetson Nano & STM32 MCU): Localized AI processing significantly reduced latency and optimized test execution speed [10].
- 5G RedCap and OPC UA over TSN for Industrial IoT Communication: High-speed, low-latency communication protocols were used to facilitate real-time synchronization between testing stations and cloud-based analytics [12].

On the software side, the system integrated:

- AI-Driven Defect Classification: Trained on 50,000+ PCB test cases, a convolutional neural network (CNN) model provided 96% defect detection accuracy [15].
- Dynamic Test Optimization Algorithms: A reinforcement learning-based decision-making system adjusted test sequences in real time, reducing false test failures by 12% [10].
- Blockchain-Based Logging for Data Integrity: Ensuring that test reports remained tamper-proof and verifiable [14].

b) Deployment Process and Challenges Encountered

1) *Step-by-Step Deployment:* The implementation of the IoT-enabled adaptive test system followed a structured deployment process:

- Hardware and Sensor Integration: Smart fixtures and industrial-grade sensors were installed and calibrated to accommodate various PCB designs.
- AI Model Training and Optimization: The defect classification model was trained using a supervised learning approach with labeled datasets to enhance detection ac- curacy.
- Edge AI and IoT Communication Setup: The real-time sensor feedback loop was established using Wi-Fi 6, 5G RedCap, and OPC UA over TSN.
- Cloud-Based Test Data Analysis and Logging: The system was linked to blockchain-based secure storage, ensuring traceability and compliance with industrial standards.

2) *Key Challenges and Solutions:* The real-world implementation encountered several challenges that were addressed through innovative technical solutions:

- Latency Issues in Real-Time Data Processing: Initial tests revealed network congestion affecting adaptive test response times. Solution: The integration of edge AI computing reduced test latency by 35%, improving responsiveness [10].
- Security Concerns with Cloud-Based Data Storage: Traditional databases posed data integrity risks in automated quality control. Solution: A blockchain-based logging framework enhanced security by 40%, ensuring that test data remained tamper-proof [14].
- False Test Failures and Calibration Issues: Some PCBs exhibited false rejections due to rigid test thresholds. Solution: AI-driven adaptive test sequencing reduced false failures by 12%, refining test precision [15].

3) Performance Evaluation and Results

The IoT-enabled smart fixture system was benchmarked against conventional test automation methods to measure its efficiency in test cycle time reduction, fault detection accuracy, and predictive maintenance capabilities. Reduction in Test Cycle Time: Traditional PCB test stations required 2.4 seconds per test cycle. The proposed system reduced this time to 1.8 seconds, a 25% improvement in test speed [10].

- Improved Fault Detection Accuracy: Conventional defect detection methods had an 87% accuracy rate. AI-enhanced test sequencing increased detection accuracy to 95% [15].
- Predictive Maintenance Efficiency: Traditional test systems required maintenance every 300 hours. Predictive maintenance techniques reduced downtime by 40% through AI-based vibration monitoring [10].
- Cybersecurity and Data Integrity: Conventional test logs were vulnerable to data tampering. Blockchain-secured logging enhanced security by 40%, ensuring tamper-proof test reports [14].

5. Conclusion

The integration of IoT-enabled smart fixtures in adaptive test automation represents a significant transformation in modern PCB manufacturing. This paper has explored the system architecture, implementation, and experimental validation of a real- time, AI-driven quality control framework, addressing long- standing inefficiencies in traditional test automation methods. By leveraging advanced sensor networks, AI-powered analytics, industrial IoT communication protocols, and blockchain- based security mechanisms, we have demonstrated how adaptive test automation can enhance efficiency, accuracy, and scalability in industrial settings.

A key contribution of this research is the development of a real-time adaptive test sequencing framework that dynamically adjusts test conditions based on AI-driven decision- making. Traditional PCB testing systems rely on fixed test sequences, often leading to false test failures or unnecessary retests. Our proposed system, through machine learning-based optimization, successfully reduced false failures by 12% while improving overall fault detection accuracy to 95% [15]. These findings align with previous research demonstrating AI's capability to improve test precision and defect classification [15]. Another significant achievement of this work is the demonstrated reduction in test cycle time. Conventional PCB test systems typically operate on a fixed-duration test cycle, often leading to wasted time on well-functioning components. Our adaptive, AI-driven approach reduced test cycle time by 25%, achieving a more efficient, responsive, and scalable testing process [10]. These improvements were facilitated by the implementation of edge AI computing, which enabled localized data processing, reducing the need for high-latency cloud- based analysis. This result aligns with findings that edge AI in industrial automation significantly improves real-time decision-making [10].

Beyond efficiency and accuracy, the proposed system introduces blockchain-based logging mechanisms to ensure test data integrity and cybersecurity. A persistent challenge in industrial quality control is the potential for data manipulation and unauthorized alterations to test logs. By integrating blockchain technology, test logs are immutable, ensuring tamper-proof records for compliance audits and industrial certification [14]. This development is especially critical as Industry 4.0 and smart manufacturing continue to evolve, requiring robust data security frameworks to maintain trust and transparency across the supply chain.

Furthermore, this research highlights the role of IoT-based communication protocols in facilitating seamless integration between test stations, AI inference engines, and cloud-based analytics platforms. The adoption of 5G RedCap, OPC UA over TSN, and Wi-Fi 6 has enabled low-latency, high-speed data exchange, allowing for real-time synchronization of adaptive test fixtures. Previous studies have demonstrated that advanced industrial IoT networks improve synchronization efficiency by up to 40% [12], reinforcing the effectiveness of our proposed system in high-mix, low-volume (HMLV) manufacturing environments.

The experimental validation of our system provides strong empirical evidence that IoT-enabled adaptive test automation is a viable and scalable solution for modern PCB manufacturing. The deployment of our smart fixture system within a real- world industrial setting confirmed its ability to adapt dynamically to different PCB layouts, improve predictive maintenance efficiency, and reduce overall operational downtime. These findings are consistent with industry trends that highlight the increasing demand for intelligent, autonomous quality control systems [9].

Looking ahead, this research lays the foundation for future advancements in fully autonomous industrial testing systems.

Several potential areas for further exploration include:

- Integration of digital twin simulations to pre-test PCB layouts in virtual environments before real-world deployment.
- Development of advanced deep learning models for

Paper ID: SR25018084546 DOI: https://dx.doi.org/10.21275/SR25018084546

finer- grained defect classification and anomaly detection.

- Expansion of adaptive test automation to multi-layer PCB and flexible electronics, enabling broader applicability across the electronics industry.

In conclusion, the study in this paper shows how IoT, AI, and smart adaptive fixtures can revolutionize PCB test automation to be more efficient, accurate, and secure. By avoiding the limitations of traditional test systems and integrating the latest AI-based optimization techniques, this paper provides a significant contribution to the overall topic of Industry 4.0 and smart manufacturing. With the current revolution in industrial automation, the innovations outlined in this paper are a blueprint to the future generation of intelligent quality control systems that are faster, smarter, and more reliable.

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