SMART REPAIR SOLUTIONS: INTEGRATING IIOT AND RECOMMENDATION SYSTEMS FOR INDUSTRY 4.0 MANUFACTURING

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ABSTRACT

Unplanned downtime and inefficiencies in traditional manufacturing systems pose significant challenges to productivity and maintenance management; to address this, smart repair solutions leverage the Industrial Internet of Things (IIoT) within Industry 4.0 environments to enable real-time diagnostics, predictive maintenance, and autonomous repair, thereby enhancing operational efficiency. By automating previously manual processes with real-time tracking, monitoring, and automated response mechanisms, the solution significantly reduces analysis and reaction times from 12 hours to 1 hour. In this paper, we propose a transformative approach to quality management with key features such as end-to-end automated monitoring, centralized information management, and scalable, self-service capabilities that support long-term sustainability.

Furthermore, the system enables automated alerts for certain high-severity defects, commonly known within the company as Severity 1 and Critical Failure Modes (CritFM), streamlining the quality control process through automated data collection, analysis, and escalation procedures. The automated alerts contain the information needed to automatically hold, prevent and contain it from impacting the quality and, in extension, reducing the carbon footprint of reworks caused by the defective parts.

1.0 INTRODUCTION

Proactively identifying and eliminating defective components before they progress through the production line or are dispatched to customers can significantly enhance manufacturing yield and key performance indicators (KPIs). More critically, it can also reduce the environmental impact associated with rework processes. However, such quality control measures are still predominantly conducted manually, which often results in defects being detected only after the components have advanced further along the production pipeline.

Smart Repair Recommendation and Tracking systems, leveraging technologies characteristic of the Fourth Industrial Revolution, have been deployed to eliminate time-intensive manual procedures, traditionally requiring approximately 12 hours, by reducing the processing time to nearly one hour. These systems contribute to operational efficiency by minimizing manual touchpoints, centralizing critical quality data, enabling real-time alerts and notifications, and supporting automated defect detection and integrated process control.

1.1 The Fourth Industrial Revolution

The Fourth Industrial Revolution (4IR) represents a technological shift marked by increased interconnectivity and smart automation, transforming industrial operations. Key benefits include autonomous operations, self-optimizing systems, improved agility, prescriptive analytics, end-to-end connectivity, resource optimization, and data-driven decision-making.

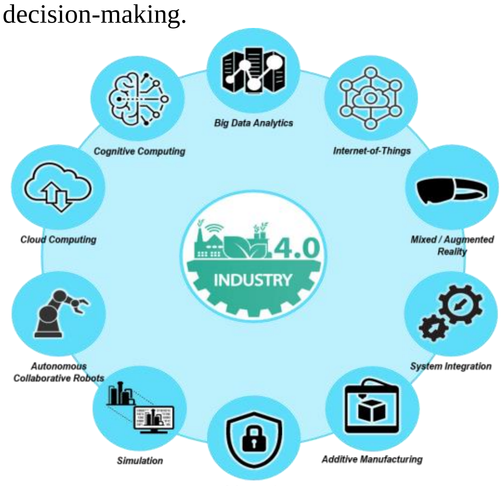

Fig. 1. List of 4IR technologies made known and readily accessible.

This project leveraged readily available solutions incorporating IIoT, system integration, and big data analytics. The integration of these 4IR technologies enabled full automation of the information acquisition process, significantly enhancing the speed and accuracy of defect detection and preventing defective components from advancing further in the production line.

1.1.1 Industrial Internet-of-Things

The Industrial Internet of Things (IIoT) is a cornerstone of the Fourth Industrial Revolution, encompassing a network of interconnected sensors, actuators, machines, and digital systems that facilitate the seamless exchange of data within industrial environments. Unlike conventional automation systems, IIoT integrates cyber-physical systems with cloud computing, edge devices, and real-time analytics to enable intelligent monitoring and control across the production lifecycle. This connectivity allows for continuous data acquisition from equipment and processes, empowering manufacturers to implement predictive maintenance, optimize asset utilization, and enhance overall equipment effectiveness (OEE)[1]. Furthermore, IIoT supports decentralized decision-making and rapid responsiveness to dynamic production demands, driving significant improvements in productivity, safety, and sustainability[2]. As such, IIoT forms the technological foundation for smart manufacturing initiatives aimed at achieving higher efficiency, quality, and flexibility in industrial operations[3].

1.1.2 Bar codes and Bar code readers

Barcodes are machine-readable optical representations of data that are widely used in manufacturing, logistics, retail, and healthcare for item identification, tracking, and inventory control. They encode information in a visual pattern that can be quickly scanned and interpreted by electronic devices, significantly reducing the time and human error associated with manual data entry. The most common formats include one-dimensional (1D) linear barcodes such as the Universal Product Code (UPC) and two-dimensional (2D) codes like QR codes, which can store larger amounts of data in a smaller space.

Barcode readers—also known as barcode scanners—are electronic devices that capture and decode the information contained in barcodes. These readers use laser, camera, or imaging technologies to scan the codes and convert the visual patterns into digital data that can be processed by a computer system. Modern barcode systems play a crucial role in enabling automation, traceability, and real-time data access in Industry 4.0 environments[4, 5].

1.1.3 System Integration

System integration is the process of combining multiple individual subsystems or components into a unified, cohesive system, enabling these subsystems to operate synergistically. This integration creates a symbiotic relationship where the overall system can achieve the desired functionality required by the organization.

When Smart Repair Recommendation and Tracking Systems are integrated, their data and analyses become synchronized, providing a single source of truth. This seamless integration ensures that the identification of defective parts is expedited, as relevant information is shared between applications, facilitating more efficient detection and response.

1.1.4 Big Data Analytics

Big data analytics involves the application of sophisticated analytical techniques to vast and heterogeneous datasets, which include structured, semi-structured, and unstructured data from multiple sources. These datasets can range in size from terabytes to zettabytes, making them challenging to manage and analyze without advanced tools[6].

In the context of this project, the data is derived from various parts and processes, with each main part has multiple subparts, with those subparts also containing subparts itself. This results in the generation of millions of data points. The volume and complexity of this data make manual processing and defect identification extremely time-consuming and inefficient. Without the implementation of big data analytics, effectively handling and identifying defects in such large datasets would be impractical[7, 8].

2. 0 REVIEW OF RELATED WORK

Several leading multinational corporations have successfully integrated RFID into their manufacturing operations. For instance, Boeing utilizes RFID to track thousands of aircraft components and tools throughout its complex assembly lines. This has improved maintenance accuracy, streamlined inspections, and helped meet stringent aviation compliance requirements by ensuring proper part usage and traceability[9]. In the automotive sector, Toyota has implemented RFID as part of its renowned Just-In-Time (JIT) manufacturing strategy. Technology allows for real-time tracking of parts across the supply chain, reduces excess inventory, and ensures timely delivery of components to the production floor, aligning with Toyota's lean manufacturing philosophy[10].

The integration of barcode systems into manufacturing assembly lines has become a standard practice among leading industrial companies to enhance traceability, operational efficiency, and quality control. For instance, BMW has incorporated barcode scanning technology within its robotic assembly lines, enabling real-time tracking of components and ensuring precision in vehicle assembly processes[11]. Similarly, Coca-Cola has implemented AI-powered visual inspection systems that utilize barcode scanning to automate the detection and correction of labeling errors, thereby minimizing production delays and enhancing product quality[12]. Automation solution providers such as Midwest Engineered Systems (MWES) have developed advanced systems that integrate automated barcode and 2D matrix code scanning, facilitating continuous tracking of work progress throughout assembly lines and improving production visibility[13]. In addition, Datalogic, a global leader in automatic data capture, provides a suite of barcode readers and identification devices employed across diverse manufacturing sectors to streamline operations and ensure consistent product identification[14]. These implementations underscore the critical role of barcode systems in modern manufacturing, contributing to increased accuracy, reduced human error, and improved production throughput.

Automated part-holding systems—commonly integrated into robotic arms, CNC machines, and smart inspection cells—play a critical role in enhancing manufacturing precision, repeatability, and throughput. These systems utilize programmable clamps, fixtures, and actuators to secure workpieces without human intervention, enabling high-speed, consistent handling of components during assembly, machining, or inspection processes. Several globally recognized manufacturers have adopted automated part-holding technologies to improve operational efficiency and reduce cycle times.

For instance, Tesla incorporates automated robotic grippers and fixtures in its vehicle assembly lines to manage the placement and securing of chassis and body components, which allows for rapid and precise alignment during welding and painting operations[15]. General Electric (GE) utilizes advanced part-holding mechanisms in its aviation and power divisions, especially in turbine blade manufacturing, where precise orientation and clamping are essential for maintaining tight tolerances during multi-axis machining[16]. Siemens, as part of its Digital Factory initiative, employs automated clamping systems in its electronics and automation hardware production lines, ensuring fast and repeatable fixturing during surface-mount technology (SMT) assembly[17]. BMW and Audi have also deployed adaptive part-holding systems integrated with vision-guided robots for their highly customized vehicle production lines, facilitating dynamic positioning and quality assurance of diverse components[18].

These examples highlight how automated holding solutions are instrumental in modernizing manufacturing systems, contributing to increased productivity, consistent product quality, and seamless integration with Industry 4.0 technologies such as real-time monitoring and intelligent process control.

3.0 METHODOLOGY

With the multitude of parts, defects and the equivalent data being generated, manually handling such data to detect defective parts and tracking the affected parts takes a lot of effort, thus the need to develop applications to be a centralized system capable of automating alerts and interlinked with a tracking system became the solution to combat this problem.

3.1 Automating and Centralizing Data

This study adopts a technology-driven approach to enhance part traceability and reduce search time within a large-scale cleanroom environment by implementing a barcode-based tracking system. Due to confidentiality agreements, specific details regarding the machine components involved have been withheld. However, the methodology described herein outlines a generalizable framework applicable to a wide range of industrial settings.

The initial phase of the implementation involves the attachment of unique barcode identifiers to each critical component of the target machine. These barcodes are affixed in a standardized manner to ensure consistent scanning accuracy and durability during handling. Once barcoded, the components are placed by an operator onto a designated storage rack system composed of multiple shelves within the cleanroom. Immediately following placement, the operator utilizes a handheld barcode scanner to read and record the barcode data for each item. This scanning process simultaneously logs the component's identification and associates it with a specific shelf or rack location in the database.

The recorded information is then transmitted in real-time to a centralized data management system that supports a custom-developed dashboard. This dashboard visually displays the real-time location of each part within the cleanroom facility, offering an intuitive user interface for operators and supervisors to monitor inventory and locate items with minimal effort. The location-tracking mechanism eliminates the need for manual searching, thereby significantly reducing non-value-added activities and enhancing overall operational efficiency.

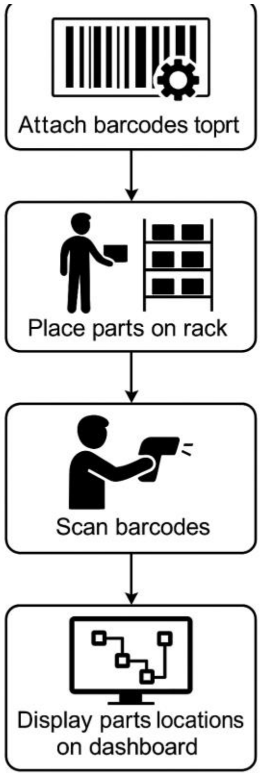

Fig. 2. To be flowchart of RFID implementation.

The methodology is iterative and designed to accommodate continuous updates. Whenever parts are moved, re-scanning is performed to update their new positions within the cleanroom. The traceability data collected also serves as a foundation for analytics, enabling further improvements in storage optimization, operator efficiency, and part retrieval times.

3.2 Standardizing the Process

Having multiple technical documentations with no standard causes major deviation between effectiveness, execution and turn-around time, thus the need to standardize and centralize it. With such chaotic data and process around repairing will take some time and the output of each repair will not have the same results every time. Not to mention the length of training a new engineer or technician will take longer as there are no standard and centralized steps.

By introducing a repair recommendation web application, technicians and engineers can have the ability to create centralized, concise, and standardized steps to perform each technical documentation encountered within or outside the pipeline. The system recommends the best practices and steps to perform for each technical documentation to be done based on the centralized library. Having standardized steps reduces the deviation of the effectiveness of the steps performed execution time and turn-around time. Repair duration will be cut down from being almost half a day to an hour or less, identifying the correct procedure will not take time and there is no deviation to the execution and training new engineers or technicians will not consume so much time due to a centralized and standardized library.

The implementation of the repair recommendation system not only creates a concise, standardized and centralized library of technical documentation steps and procedures but also contributes to lessening the unnecessary requests for unneeded materials or tools to be used, effectively reducing another aspect that contributes to the reduction of carbon footprint and waste.

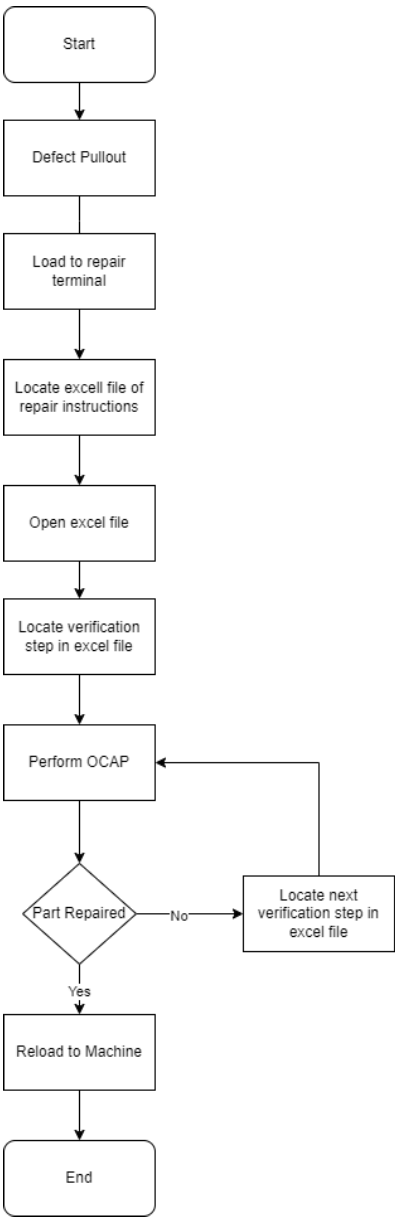

Fig. 3. Before implementation of Repair Recommendation System

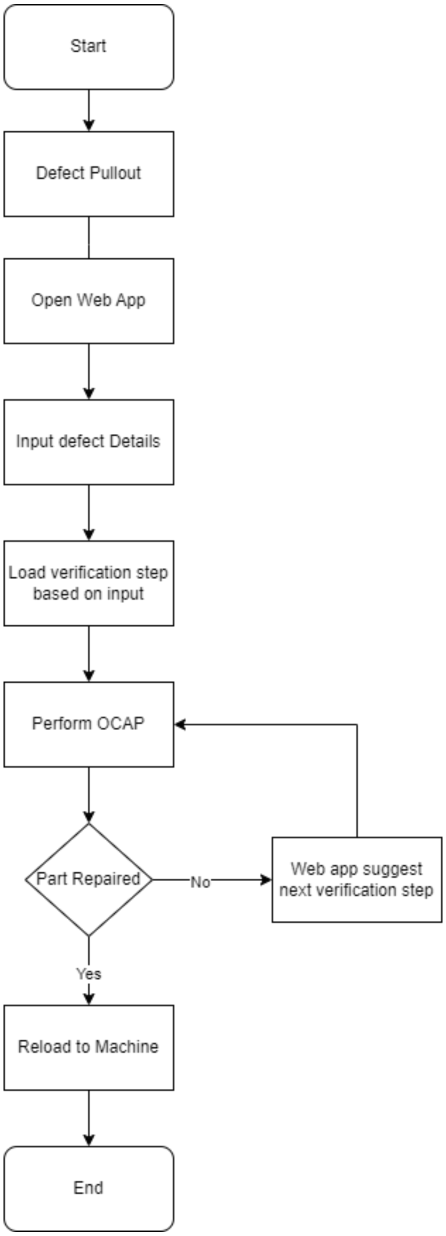

Fig. 4. After implementation of Repair Recommendation System

4.0 RESULTS AND DISCUSSION

Using the approaches described in this paper's earlier section, the turn-around time of defect identification has been reduced significantly from half a day to an hour.

Activity	Unit	Without Repair Recommendation System	With Repair Recommendation System
technical documentation Identification	Hours	2	0.5
Repair Time	Hours	12	1

Table 1. Time improvements upon Implementation

5.0 CONCLUSION

In conclusion, due to the technologies and solutions put in place efficiency, tracking of defective parts has increased significantly before when it was done manually. Since the data is centralized, methods and steps for repairs of the technical documentation has been streamlined.

6.0 RECOMMENDATIONS

With the success of this project, the Smart Repair Recommendation and Tracking systems are considered to be implemented across the processes in the shopfloor for a fully automated tracking and concise, standardized and centralized technical documentation.

7.0 ACKNOWLEDGMENT

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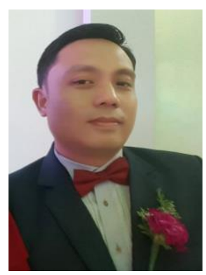

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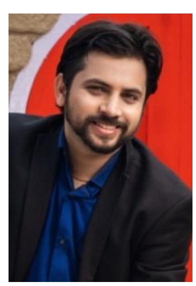

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