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Development of an SPC Platform for High-Precision Aerospace Components Through Automated Collection of 3D Measurement Data and Report Automation

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ABSTRACT
As the Fourth Industrial Revolution continues to expand across various industries, many companies are accelerating efforts to establish smart factory-based industrial environments. A smart factory refers to an intelligent production system that maximizes efficiency and productivity by integrating digital automation into every stage of production, including design, manufacturing, quality control, and logistics. This innovative system is particularly significant in the high-precision aerospace component manufacturing industry, where the importance of meeting stringent quality standards is paramount.

The high-precision aerospace component industry demands extremely high-quality standards, and to meet these requirements, precise measurements using three-dimensional (3D) measurement machines have become an essential part of the production process. Accurate data collection through 3D measurement machines plays a crucial role in ensuring product quality. However, traditional methods of data collection and management have heavily relied on manual processes, which are time-consuming, labor-intensive, and prone to human error, leading to limitations in productivity and quality control.

To address these challenges, this paper proposes the design and methodology for developing a Statistical Process Control (SPC) system platform specifically tailored for the real-time automatic collection and analysis of 3D measurement data in high-precision aerospace manufacturing processes. The agent developed in this research enables the real-time automatic collection of raw data, offering significant advantages in terms of labor and time savings compared to traditional manual methods. This agent automatically compiles and analyzes data, facilitating optimized quality verification processes for high-precision aerospace component manufacturing.

The collected quality data are analyzed using statistical quality control techniques specialized for 3D measurement data, allowing for continuous monitoring of product quality. Additionally, the system supports the establishment of a quality monitoring system capable of real-time response to any quality issues that may arise, significantly enhancing the efficiency of quality management. Therefore, the system proposed in this paper provides the essential technological foundation for implementing smart factories in the high-precision aerospace component manufacturing industry, with the potential to greatly improve overall productivity and quality management efficiency. This research is expected to make significant contributions to quality management in smart manufacturing environments for high-precision components.

Keywords: CMM, SPC, Automated Data Acquisition, Quality Control, Inspection Report

1. INTRODUCTION

Precision measurement is defined as the process of comparing quantities such as dimensions, angles, surface roughness, and geometric tolerances of high-precision machined components against other units of measurement[1]. Measurement is one of the three critical elements in the machinery industry, along with design and processing. A 3D measuring machine is a device that detects spatial coordinates of each measurement point by moving a probe that measures the surface position of an object in three-dimensional space. The data collected is processed by a computer to measure three-dimensional attributes such as size, position, or orientation[2]. Compared to traditional 2D measurement methods, 3D measuring machines offer several advantages, including reduced measurement time, improved measurement efficiency, elimination of measurement errors associated with the measuring tool, simplification and reliability, and enhanced precision quality control. These machines are currently most widely used in the automotive industry and are also predominantly employed in the plastics industry, semiconductor component industry, and aerospace industry[3,4].

Statistical Process Control (SPC) refers to the method of analyzing data in real-time to monitor and regulate manufacturing processes[5,6]. SPC is a statistical methodology used to manage and improve process quality in both manufacturing and service industries. The goal of SPC is to analyze variability occurring in processes and control it to maintain or enhance the quality of products or services. In particular, in high-precision aerospace component machining companies, SPC systems are extensively utilized for efficient quality management and problem-solving.

In the high-precision aerospace component machining industry, precision measurement using 3D measuring machines is conducted through a 100% inspection approach, in contrast to the sampling methods used in quality inspections in other industries[7]. Consequently, while many companies are making efforts to reduce lead times in inspection processes, automated collection and analysis of complex 3D measurement data are not yet effectively implemented. The current quality inspection process involves manually collecting data from 3D measuring machines in a highly limited manner and manually entering quality measurement data into PCs, which increases operator fatigue and human resource demands. Additionally, the need to organize and document data based on measured results lowers the reliability of inspection outcomes and introduces challenges in the work environment.

In the high-precision aerospace component machining industry, quality is critically linked to safety, necessitating very stringent quality inspections. Consequently, the quality measurement process using 3D measuring machines is an essential procedure rather than a sampling process. To ensure precise measurements without human error, quality assessments are conducted using automated 3D measuring machines[8].

In the high-precision aerospace component industry, the quality inspection process involves analyzing the raw data generated from measurements taken by 3D measuring machines. Quality managers then reprocess this data to create inspection reports. Figure 1 illustrates the quality inspection process for high-precision machined components. After machining, the operator of the 3D measuring equipment creates a measurement macro program based on the drawings, applies this program to the 3D measuring machine, and conducts the measurement. The inspection result files generated after measurement can be produced in various formats such as Excel files or ASCII data, depending on the manufacturer of the 3D measuring machine. The quality manager analyzes these files using Excel applications and subsequently prepares the inspection reports.

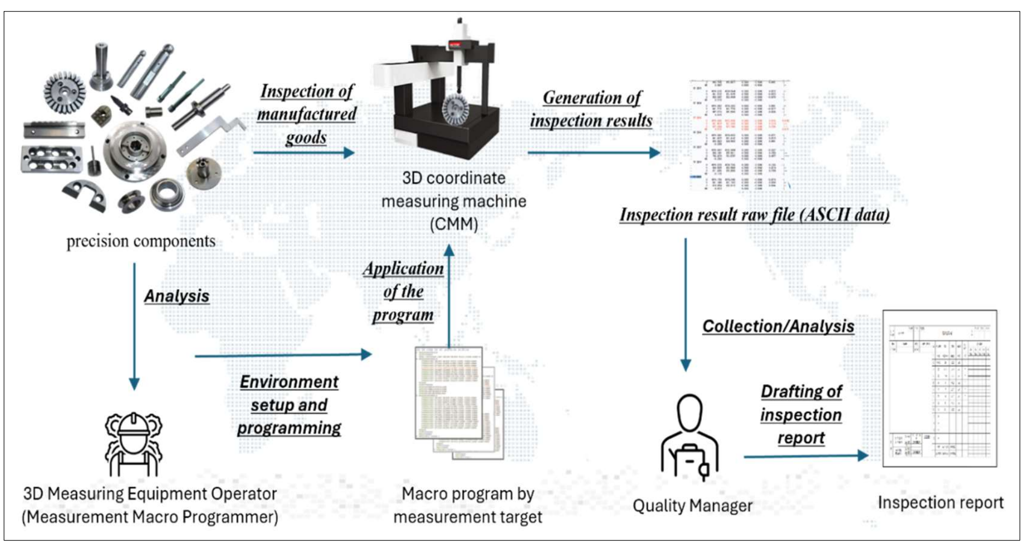

Figure 1: Inspection Processes for High-Precision Aerospace Components

In particular, aerospace components are processed and measured sequentially according to the drawings: one machining process is completed, followed by measurement, and then subsequent machining and measurement are carried out. This approach allows for the detection of errors such as distortions occurring from earlier processes in the later machining steps. The time required for this process is referred to as the quality process lead time. Reducing the lead time of the quality inspection process is directly linked to cost reduction, and therefore many companies are exploring various strategies to shorten this lead time.

Statistical Process Control (SPC) is a management approach used to statistically measure and evaluate whether the characteristics of produced products or services meet design specifications, thereby determining whether the quality level of the process is being effectively managed. The goal of SPC is to improve quality. By managing the production process using SPC, Process Variation can be reduced, resulting in more uniform products[9].

To implement Statistical Process Control (SPC), various types of quality data are required. In particular, quality data from 3D measuring machines provides valuable and meaningful information that can be used for detecting process anomalies and quality predictions. By applying statistical management techniques to the information produced, it is possible to improve process capability on the production floor, enable automatic prediction and prevention of process anomalies, enhance workability, and ensure stable quality[10]. Figure 2 illustrates the significance of the variability intervals for process stabilization.

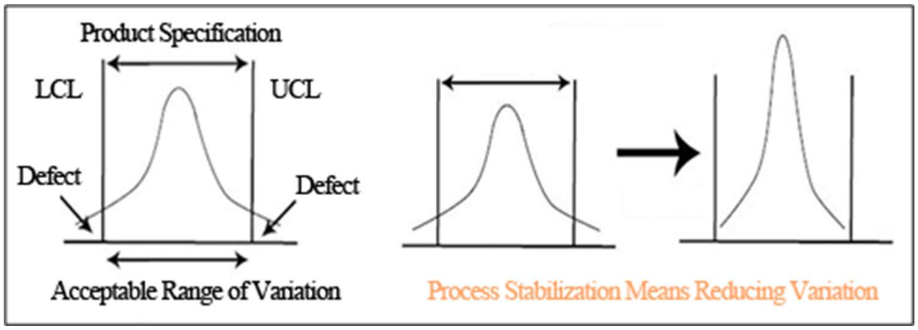

Figure 2: The Meaning of Quality Variability

In the ultra-precision field, SPC systems require high accuracy in interpreting and analyzing variations around the center and variability, as shown in Figure 3. The following Figure 3 presents the evaluation criteria for SPC systems utilizing 3D measuring machine data.

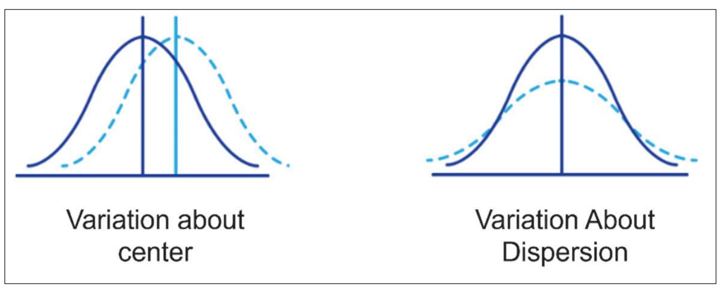

Figure 3. Evaluation Criteria for SPC Systems Using 3D Measuring Machine Data

The purpose of this paper is to use advanced ICT technology to develop a real-time automatic collection agent that relies on manual data through Raw Data analysis to dramatically save input and transportation, and to develop an SPC system optimized for the high-precision aviation parts industry through statistical quality control techniques dedicated to 3D measurement data[11]. In addition, a quality monitoring system was established to display issues and risk information such as process status and cause of failure through real-time measurement data monitoring.

This paper is organized as follows: Following the current introduction, Section 2 presents a review of research related to 3D measuring machine inspection processes and SPC systems. Section 3 describes the components and key aspects of the developed system. Section 4 presents the results and performance of the proposed system. Finally, Section 5 concludes with a summary and outlines future research directions.

2. MATERIAL & METHODS

2.1. *Overview of proposed system*

In this paper, we propose an SPC and real-time monitoring system utilizing quality measurement data from high-precision aerospace components. The proposed system enhances the reliability of quality measurement results, reduces labor resources, and improves stable quality capabilities through quality data analysis. Figure 4 illustrates the overall structure of the proposed SPC platform. The system operates as follows: Raw quality data measured by the 3D measuring machine is acquired in real-time through an analyzed algorithm and transmitted to the server, where it is stored in a database. The stored quality data is then made available to quality managers via a web-based SPC system, offering various statistical analysis tools for continuous quality process management[12]. Additionally, the system provides real-time monitoring through the real-time acquisition of quality data.

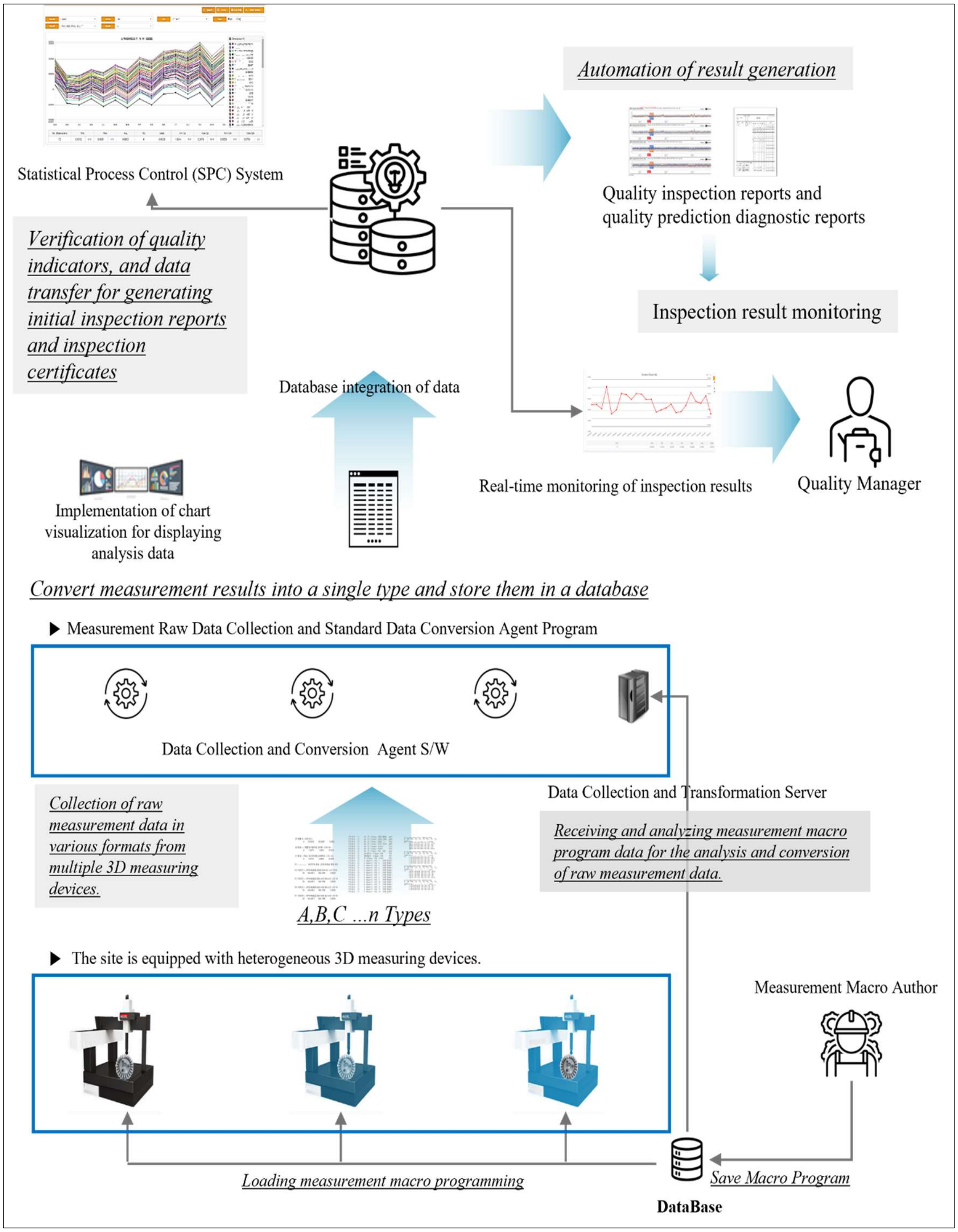

Figure 4. Proposed SPC Platform Architecture

The hardware specifications of the system used in this study are listed in Table 1.

Table 1 : System Specifications Used for Testing

SYSTEM	SPECIFICATIONS
3D Measuring Machine(Model)	DUKIN Co,. Ltd. (VICTOR)
3D Measuring Machine Control PC	HP Desktop (NeuroMeasure)
DataBase	MS-SQL 2018
OS	Windows Server 2022
DB & Web Server	HP DL360 Serise

2.2. *3D Measuring Machine Data Automatic Collection Agent*

Raw data from 3D measuring machines is inherently difficult to analyze and requires complex processes to extract the information necessary for analysis and decision-making. However, all measurement results universally contain essential numerical geometric information and various inspection details. To address this, an agent was developed to collect this raw data information, and a standard format for the measurement results was defined. Tools were also developed for storing and validating the data according to this standard. Figure 5 illustrates the process of real-time data collection, both automatic and manual, as installed on the PC of the 3D measuring equipment.

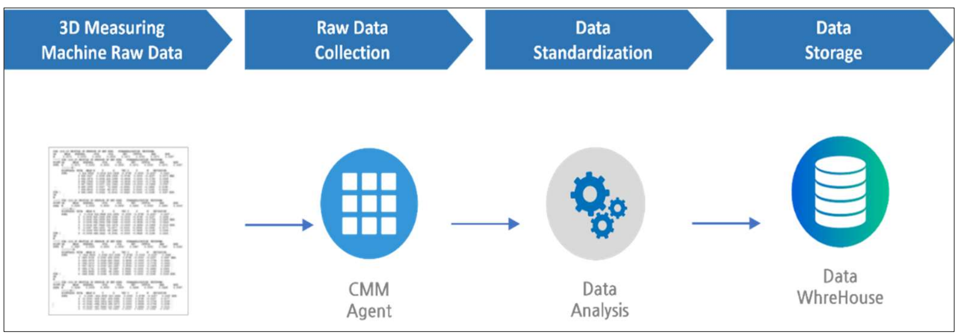

Figure 5. 3D Measuring Machine Data Collection Process

Step 1: 3D Measuring Machine Raw Data

This stage involves identifying the dimension number and detailed description of the measured area from the measurement result files through data pattern matching. It then extracts relevant information such as Actual, Nominal, Upper Tolerance, Lower Tolerance, Deviation, and judgment values for the specified area.

Step 2: Raw Data Collection

In this stage, the data extracted from the previous step is organized based on the Shop Order (S/O) and categorized by measurement type (normal/re-measurement/rework). The data is then checked for duplicates, objectified, and temporarily stored.

Step 3: Data Standardization

This stage involves validating the integrity of the temporarily stored data and checking for duplicates and errors with the measurement results stored in the database. It includes a functionality to convert the data to the standardized format.

Step 4: Data Storage

This stage involves storing the validated and standardized data into the actual database. Since 3D measurement results can generate hundreds to thousands of data points from a single measurement, the data is partitioned in the database according to specific criteria (such as time period, product type, etc.). This partitioning ensures that the system's performance is maintained when the data is utilized in SPC.

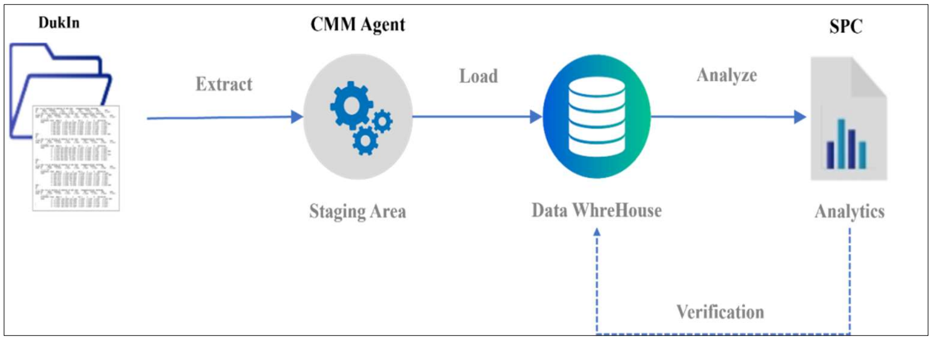

Figure 6: 3D Measuring Machine Data Analysis Process

Figure 6 illustrates the process of analyzing 3D measuring machine data. The data extracted from the measurement results undergoes validation to ensure its integrity by checking for incorrect patterns, missing data, and duplicates, among other issues. Additionally, based on the collected data, process monitoring information and CPK are automatically calculated to facilitate monitoring. This stage also marks the starting point for real-time monitoring tasks integrated with Back-End services[13].

2.3. SPC System Dedicated to 3D Measuring Data

The 3D measuring machine dedicated SPC system proposed in this paper comprises three components: a data validation tool, a data analysis tool, and a real-time monitoring tool.

2.3.1. Data Validation Tool

The data validation tool provides functionalities to search real-time collected 3D measurement raw data based on various search criteria and to interface with other external quality analysis systems. Figure 7 shows an example screen of SPC data validation for collected raw data, including typical shapes as well as Blade and Blisk shapes in aircraft engine components[14].

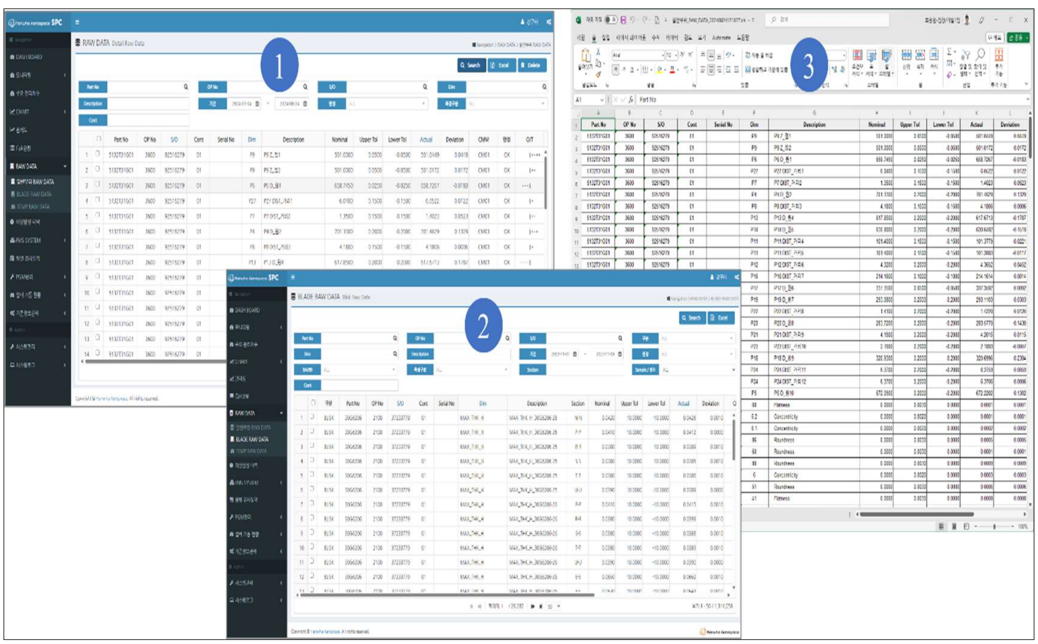

Figure 7: SPC Data Validation Tool

① The raw data validation screen for general shapes provides functionalities to search and validate collected raw data using various search criteria such as Part No, Process No, Shop Order (S/O), Dimension, Description, Judgment Results (pass/fail), Measurement Type (normal/re-measurement/rework), and Measurement Date.

② For Blade and Blisk shapes, in addition to the search conditions used for general shapes, the tool provides additional functionalities to search and validate collected raw data based on additional criteria such as Section and Sample Count.

③ The tool offers the capability to export collected raw data for both general shapes and Blade and Blisk shapes to Excel, allowing for cross-validation with other quality analysis tools (e.g., Mini-Tab) and systems.

2.3.2. Data Analysis Tool

The data analysis tool provided by the developed system offers various analytical capabilities optimized for the high-precision aerospace field. It supports diverse analyses under various conditions using different charts. Figure 8 illustrates representative SPC data analysis examples, including Run Charts, Single Charts, Blade Charts, and Box Plots.

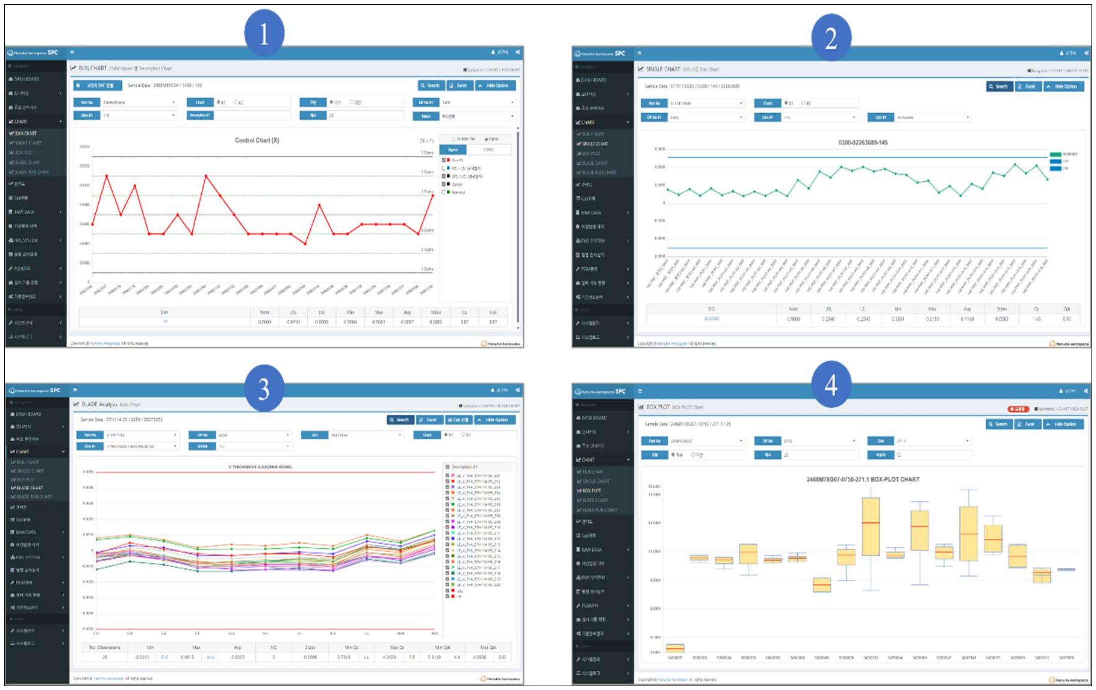

Figure 8: SPC Data Analysis Tool

① **Run Chart:** This tool analyzes the quality of a product by examining measurements of the same dimension for the same product over the most recent 25 data points or a specified time period. It helps determine whether the measurements fall within the control limits and the extent of deviation within those limits. The Run Chart is a primary tool for trend analysis and evaluation of the product's quality at specific measurement points.

② **Single Chart:** This tool provides quality analysis for identical shapes within a product, such as 30 holes of the same shape in one product. It allows for detailed quality analysis by offering metrics such as minimum, maximum, average, standard deviation, Cp, and Cpk for the measurements of the same location. This facilitates a more granular quality analysis.

③ **Blade Chart:** This tool is used for analyzing components such as turbine blades in engine parts. Since each blade is managed with high precision and has the same shape, the Blade Chart allows for comparison and analysis of measurements across different blades, shop orders (S/O), and sections.

④ **Box-Plot:** This tool summarizes the distribution of a dataset, displaying the interquartile range (IQR) which covers the middle 50% of the data. The line within the box represents the median, while the "whiskers" extending from the box indicate the minimum and maximum values. Points outside these whiskers are considered outliers. The Box-Plot is a valuable quality analysis tool that provides a clear view of data distribution, central tendency, and variability.

2.3.3. Real-Time Monitoring Tool

The Real-Time Monitoring Tool provides functionality for simultaneous monitoring and tracking of the stability and anomaly detection of the process alongside the collection of 3D measurement data. When an anomaly type is detected through real-time monitoring, immediate notifications are sent to the responsible personnel, allowing for prompt actions based on the analysis tools mentioned earlier. Figure 9 illustrates the real-time process monitoring screen where anomaly detection has occurred.

Figure 9: Real-Time Monitoring Tool

Real-time process monitoring is facilitated through the CMM Agent, which automatically collects data. This feature provides real-time notifications and monitoring screens for administrators, alerting them to defects that fall outside the specified control standards for the product and process. Beyond simply identifying defects, the system also monitors and alerts administrators in real time for four predefined anomaly patterns, even if the products are within specification. This capability enhances the level of quality analysis and process management. The four types of anomalies are defined as follows:

1. When a single point falls outside the control limits (mean ± 3σ).
2. When there are nine consecutive points appearing on one side of the mean (within the control limits of mean ± 3σ).
3. When there are six consecutive points that consistently increase or decrease (within the control limits of mean ± 3σ).
4. When there are fourteen consecutive points alternating between increases and decreases (within the control limits of mean ± 3σ).

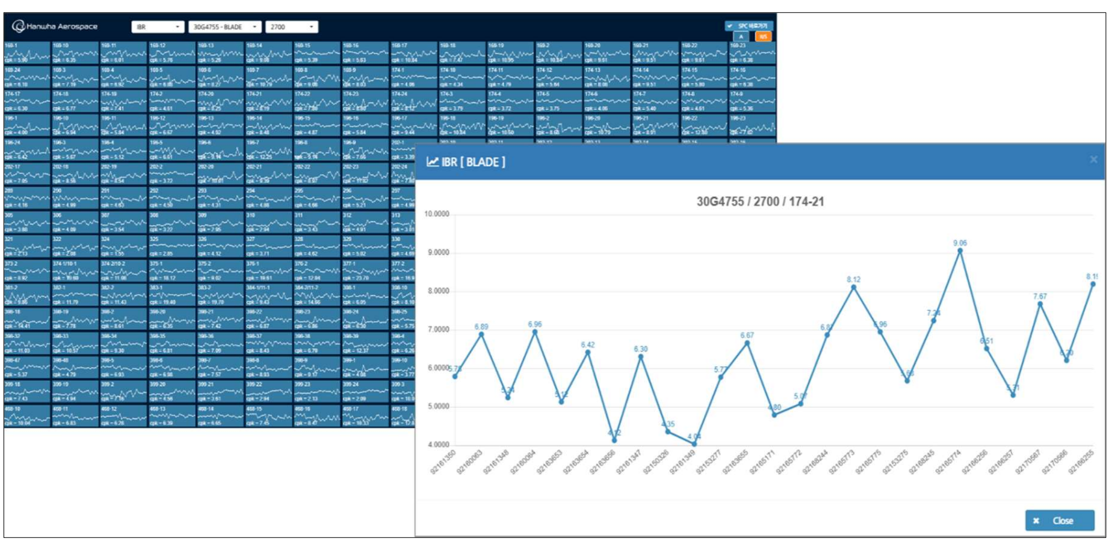

Figure 10. CPK Monitoring

Figure 10 illustrates an example of CPK monitoring. The CPK monitoring screen provides functionality to automatically calculate CP and CPK based on the most recent 25 data points collected through the CMM Agent, allowing for real-time monitoring of process stability. The system displays how consistently the product is being produced within specification limits, presented in a chat format for easy interpretation. This makes it a highly suitable tool for real-time assessment of process variability[15].

3. RESULT & DISCUSSION

The most critical aspect of this study is the automation of raw data acquisition from 3D measuring machines and the establishment of an SPC system utilizing the acquired measurement data. Prior to this research, manually converting approximately 10,000 lines of raw data from a 3D measuring machine into a database took between 1 to 2 hours. With the developments made in this study, this process has been reduced to under 1 second. This advancement has significantly shortened the quality process lead time, which has long been a challenge in the high-precision aerospace industry. Table 2 compares the time required for raw data acquisition and report generation before and after the system development. The inspection report is a document that expresses the dimensions of the machined parts in a standard format after the machining process. Depending on the client's request, it may include not only simple dimensions but also averages or variances of the dimensions. The test involved comparing the time required to manually convert raw data into a database with the time required for automatic database conversion. Additionally, the time for generating inspection reports manually from result files compared to automatic report generation using database data was measured. The products used in this test had result files with 10,000 lines, 20,000 lines, and 30,000 lines of measured raw data, respectively.

Table 2: Test Results

Rowdata count	Data Analysis & Acquisition Time		**Report Generation Time**	
	Before Implementation	**After Implementation**	**Before Implementation**	**After Implementation**
10,000 line	60 min.	0.7 sec	4 Hours	0.9 sec
20,000 line	70 min.	0.8 sec	4.5 Hours	1.0 sec
30,000 line	80 min.	0.9 sec	5 Hours	1.1 sec

Additionally, a dedicated SPC system platform for 3D measurement data was developed using the database-converted measurement data. This development achieved full automation of the process, which previously involved manually creating Excel files from raw data and calculating quality metrics using programs such as Mini-Tab. As a result, significant improvements in accuracy and quality were realized.

4. CONCLUSION

This paper presents the development of a system for automatically acquiring raw data from 3D measuring machines and an SPC system utilizing the acquired measurement data. The objective of this research is to develop an automated system for data acquisition and analysis, which previously relied on manual processes. To achieve this, an automated data acquisition agent and a dedicated SPC system for 3D measurement data were developed. The performance of the system was evaluated by comparing the automation time with the average manual time. The results show a significant reduction in lead time due to automation. As the performance evaluation of the proposed SPC system has been conducted with a specific company, further research is needed to analyze raw data from a wider range of 3D measuring machine manufacturers and expand its applicability to more models.

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