Automatic Quality Control System for Aircraft Assembly during the Whole Life Cycle Based on Digital Twin

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Abstract—**Alignment of aircraft components is crucial in the assembly process, involving the collaborative work of measurement and control systems, and the alignment quality directly affects the assembly qualification rate and rework rate. Currently, the quality assessment mainly relies on manual experience and lacks automated control means, making it difficult to realize accurate traceability of alignment quality. Based on this, this paper proposes a digital twin-based automated control method for whole life cycle aircraft assembly quality data, which improves the efficiency and reliability of alignment quality analysis. Firstly, the distribution of quality data in the aircraft alignment process and how it is specifically applied are sorted out. Secondly, a multi-tier architecture of the digital twin system was constructed. The automated categorization stores and evaluates the quality data in the alignment process during the whole life cycle of quality data acquisition, analysis, and utilization. Dynamic twin monitoring of real-time quality data is based on assessment results. Effective traceability and dynamic control from quality data to process are achieved by visualizing alignment quality throughout the aircraft assembly life cycle.**

Keywords—Aircraft Assembly, Real-time, Anomaly Detection, Process Data, Industrial Automation, Digital Twins

I. INTRODUCTION

As a strategic high-tech industry of the country, the development level of the aviation manufacturing industry has become one of the important indicators for evaluating the scientific research strength, industrial manufacturing capacity, and international influence of the country [1]. Aircraft manufacturing occupies a key position in this field, which not only represents the cutting edge of aerospace manufacturing technology but also presents significant complexities and challenges over traditional machining.

Aircraft component alignment is a crucial link in aircraft assembly, which directly determines the safety and service performance of aircraft products. The workload of this process is relatively large, accounting for more than 50% of the entire aircraft manufacturing workload [2]. During the alignment process, the equipment is capable of generating real-time data containing information about the quality of the alignment. These data are tightly coupled with the precise mapping of the process and can be utilized to calculate the part's position in real-time, identify anomalies, assess the quality of the alignment, and propose solutions accordingly.

To obtain more accurate data during the alignment process, various aerospace manufacturing companies have introduced a digitalized, high-precision attitude alignment system [3]. This system is capable of performing linear fitting and shortest path calculations in a timely and precise manner, thereby facilitating the achievement of attitude alignment [4]. However, in the current aircraft attitude alignment process from various segments to complete aircraft assembly, the alignment quality data are distributed in multiple attitude alignment systems. There are many sources of data in inconsistent formats and a lack of centralized storage and management solutions [5]. This fails to effectively reflect the correlation between data and hinders the sharing and reuse of data and information. In addition, the disconnect between design data and manufacturing data further reduces the reusability of process data. It is difficult to support design optimization of multiple aircraft products with manufacturing process quality data [6]. Faced with the complexity of the assembly process, the need for multidimensional information exchange, and the synchronization of resources, traditional quality control methods show their limitations. Its over-reliance on manual experience accumulation makes aircraft manufacturing quality control a serious challenge [7].

The above problems hinder the sharing and reuse of data and affect the efficiency and accuracy of aircraft assembly quality control. Digital twins, a cutting-edge technological tool, can solve these problems. By integrating virtual reality technology, computer graphics, artificial intelligence technology, and simulation technology [8], the attributes, methods, behaviors, and other characteristics of physical objects are digitally modeled in virtual space [9]. By creating a virtual entity that corresponds exactly to the physical entity, the state, and performance of the physical entity can be reflected in real-time. The application of this technique provides the possibility to achieve virtual physical interaction, data fusion, decision analysis, and iterative optimization based on assembly quality data [10].

This paper analyzes the specific application of quality data in the process based on digital twin technology, obtains quality data of the part alignment process, effectively evaluates the quality of part alignment, and realizes dynamic twin monitoring.

II. Quality Data and Application in the Alignment Process

The attitude adjustment alignment process plays a vital role in aircraft assembly and manufacturing, which ensures the precise assembly of aircraft components and guarantees the performance of the whole aircraft. This process realizes the precise fit between components by fine adjustment of the spatial position of aircraft components. During the attitude alignment process, critical quality data can be collected and analyzed during the measurement, attitude, and alignment processes. This includes data from the horizontal measurement points, position data from the positioning mechanism, and three-dimensional force data from the force sensor. These data characterize the quality of the alignment and provide a basis for quality assessment and decision support through specific applications for different craftsmen. In-depth analysis and effective use of these multi-dimensional quality data can significantly improve assembly accuracy, optimize production processes, and enhance the safety and reliability of aircraft products.

To better understand the specific role of quality data in the attitude adjustment and calibration process, the following section organizes the process flow and discusses the particular applications of this quality data, as shown in Fig. 1.

Firstly, the component is racked to the CNC positioner. The laser tracker was utilized to measure the ground ERS points to establish the measurement field and record the horizontal measurement point data. Subsequently, the component attitude adjustment alignment process was started. By adjusting the positioner, the component to be docked was brought close to the theoretical positional attitude, while the positional data of the moving mechanism was recorded. These data provide positional references for the parts to be docked and the initial position of the docked parts. The surveyor can display the results of the component's horizontal measurement point measurements, evaluate multiple horizontal measurement point errors, and export measurement point analysis results in the system. Ultimately, it can be determined whether the part attitude meets the process requirements.

Secondly, the positioner will drive the alignment component to the alignment area during the rough adjustment phase. Accurate alignment is ensured by measuring its position again. The operator of the attitude adjustment and alignment system will judge whether the alignment directional force exceeds the threshold value, and check the real-time force sensor data of multiple positioners in this phase. Based on this, the operator will determine whether the alignment interference occurs and adjust the alignment strategy. Thereafter, the fine-tuning phase begins and the operator continues to observe the three-dimensional force data from the locator end force sensors of the support component to prevent interference situations. After each fine tuning, the attitude of the docked component is re-measured until the coordinates of all horizontal measurement points meet the process specification error margins. When these accuracy requirements are met, it can be determined that the component attitude has been adjusted to the theoretical attitude, and the accurate alignment of the component is completed.

In this process, the alignment system automatically records a detailed process log based on the operating instructions, which contains the specific steps performed during the alignment process and the accompanying quality data. Data analysts can obtain multi-shelf alignment data, query specified categories of quality data, and export specified periods of data for in-depth analysis of process logs. Data analysts can obtain multi-shelf alignment data, query specified categories of quality data, and export specified periods of data for in-depth analysis of process logs. This allows precise tracking and localization of any anomalies in the real-time data, enabling rapid diagnosis and effective management of the source of the problem. It can also be used to analyze data trends and improve processes.

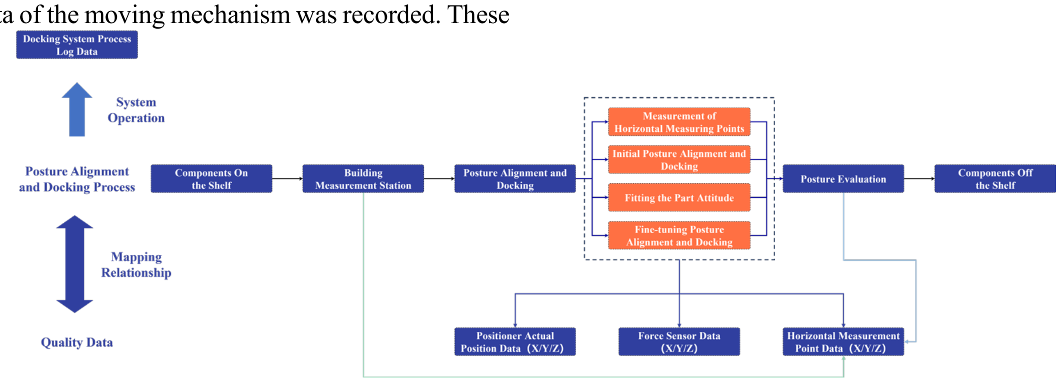

Fig. 1. Aircraft component alignment and alignment process

The analysis of the specific application of quality data demonstrates its importance in guaranteeing the accuracy and reliability of the aircraft assembly process. It helps to find and solve potential quality problems in time and can significantly improve the overall quality and productivity of aircraft assembly.

III. System Architecture

Based on the corresponding process requirements of each link of the above process, a whole life cycle quality data automation control system for the aircraft component docking process is constructed to analyze and control the process effectively. The overall architecture of the system is shown in Fig. 2, which is mainly composed of the device layer, quality data layer, protocol layer, data storage layer, quality data analysis layer, and data application layer. To express the life cycle of quality data in the aircraft assembly process more effectively, this paper will focus on three major parts: data acquisition and storage, quality data analysis, and digital twin application. The specific functions of each part are as follows:

A. Data Acquisition and Storage

The OPC UA protocol is applied to the attitude control system to unify the heterogeneous data transfer formats of positioners, laser trackers, and force sensors on the aircraft assembly line. Subsequently, an integrated multidimensional quality data interface is used to obtain process data characterizing the quality of the attitude adjustment and alignment. Based on this interface, the data server reads the real-time data from the device and saves it in a time series database. Specific categories of process data can be read from the time series database and stored in the relational database via the software interface as required. In this process, the log data parsed by the attitude alignment control system is also imported and stored in the relational database for further analysis and utilization. The dynamic and static quality data of the whole life cycle of the alignment process are collected and stored in the above way.

B. Data Quality Analysis

Multiple types of quality data are analyzed and evaluated according to process indicator requirements. The system performs anomaly detection of force sensors based on the force threshold of the positioner. At the same time, the deviation of the horizontal measurement points is evaluated based on the numerical modeling theory of the tuning points. By parsing the process logs, specific operations in the alignment system that lead to quality problems can be traced and analyzed. This process ensures the accuracy and traceability of process requirements and improves the precision and reliability of quality data analysis.

C. Digital Twin Applications

The system interacts with the visualization interface via a browser client, generating dynamic graphs to monitor process data. Meanwhile, the Unity3D client interacts with the digital twin interface to realize digital twin motion simulation based on real-time data. Users can monitor process quality data through two different clients for twinning, thus realizing accurate process control.

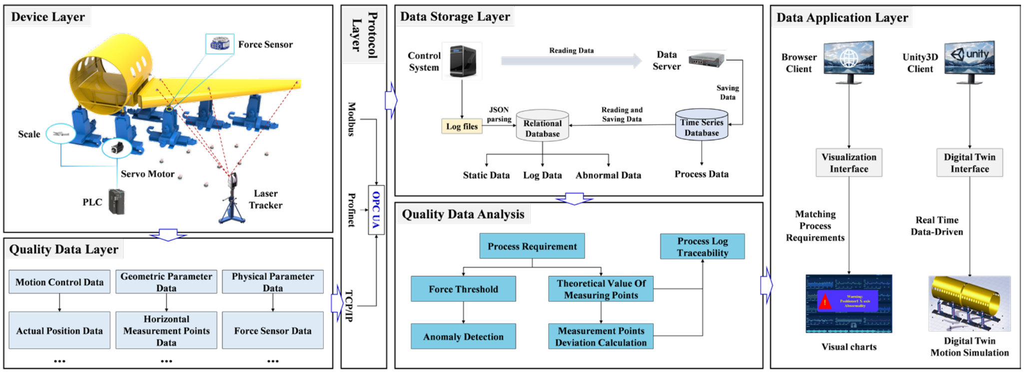

Fig. 2. Framework for an automated control system for full life cycle quality data

IV. Quality Data Assessment and Real-time Digital Twin Monitoring

The system provides real-time monitoring in the form of dynamic visual graphs and digital twins by mapping process data to behavioral logic. This approach ensures that the docking process and its associated information are continuously and synchronously tracked throughout the lifecycle [11]. This method not only captures and analyzes various data in the production process in real time but also responds quickly when anomalies occur. Through timely adjustments and corrections to ensure the stability and reliability of the process.

Using the system framework shown in Fig. 2, an assessment and monitoring platform integrating multiple categories of quality data was constructed. The platform provides real-time monitoring and management of the process through data evaluation algorithms. Combined with digital twin technology, the platform not only records and analyzes static data, but also dynamically monitors production and provides real-time feedback and forecasts, enhancing the efficiency and accuracy of quality management.

A. Quality Data Assessment

1) Quality Analysis of Abnormal Data from Force Sensors

A data quality analysis method based on force sensor thresholds has been introduced to ensure that damage does not occur to components due to excessive force, as shown in Fig. 3. By comparing the real-time collected force sensor data with a pre-set process threshold, it is possible to determine whether the part has been subjected to a force that exceeds the process threshold. Force sensor data that exceeds the process threshold is flagged as abnormal. With the abnormal data processing function in the system, it is possible to record and display key information such as the specific workstation that generated the abnormal data and the time when the abnormality occurred. By analyzing the abnormal data, it is possible to accurately determine which components have failed to meet the process quality requirements. The operator can quickly take measures to adjust the alignment strategy to ensure the quality and safety of the entire assembly process.

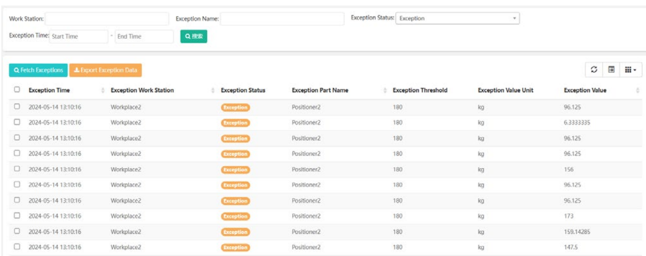

Fig. 3. Force sensor data quality analysis interface

2) Quality Analysis of Measurement Data

During the attitude adjustment and alignment process of an aircraft component, accurate determination of the component's attitude is critical to ensure the quality of the alignment. This process is achieved by acquiring the component's horizontal measurement point data through a laser tracker. These data are solved by SVD to determine the spatial attitude of the component. To assess the quality of the alignment, the horizontal measurement point data acquired in real time needs to be compared with the theoretical data. By calculating the deviation as well as the symmetry of the horizontal measuring points on both sides, it is possible to quantitatively assess whether the data from the horizontal measuring points are within the tolerances required by the process indicators, as shown in Fig. 4. If the deviation is outside the tolerance range, it indicates that the attitude of the component does not match the design requirements and the docking quality fails to meet the standard. The operator needs to fine-tune the positioner to meet the process requirements based on the deviation data.

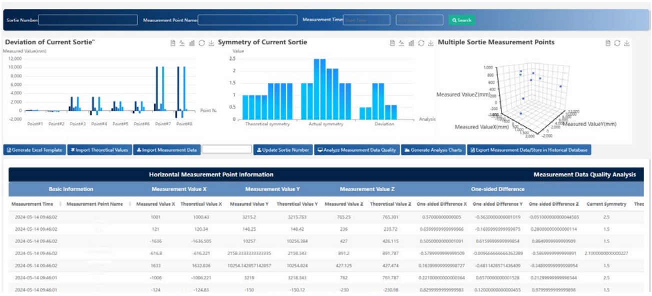

Fig. 4. Measurement data quality analysis interface

3) Quality Analysis of Process Log Data

During the aircraft attitude alignment process, the process log records the complex process steps and key quality data of the attitude alignment system in detail, as shown in Fig. 5. The quality data set of the specific operation process is formed by structuring the log files and classifying and storing them according to the process steps. The system monitors real-time data collected from force transducers and horizontal measurement points and analyses the associated matching operational process quality data sets when outliers or exceedances of process specifications are detected. It is possible to trace the specific process steps and their corresponding operations that led to the component alignment quality problem. This analysis process not only helps to identify and eliminate anomalies and adjust the operation of the process equipment that needs to be improved but also ensures the quality and stability of the docking process.

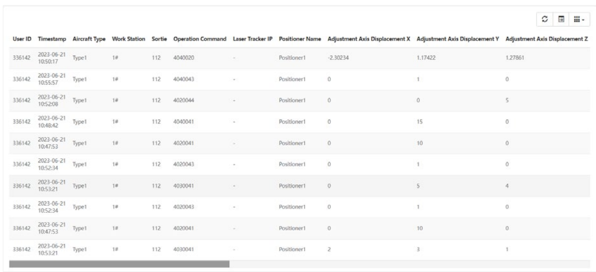

Fig. 5. Process log data quality analysis interface

B. Dynamic Visualisation Monitoring

1) Visual Monitoring of Abnormal Force Values

To ensure that the aircraft parts during the attitude adjustment and alignment process do not interfere with the collision and damage the parts, it is necessary to detect in real time whether the force sensor data of multiple positioners exceeds the process threshold. The real-time acquired force sensor data is displayed in the form of a visual graph, as shown in Fig. 6. The graph is dynamically updated to reflect the real-time data changes, and the abnormal values of the force sensors exceeding the preset range are instantly detected. According to the abnormal values, it can be judged whether it is necessary to operate the attitude control system to stop the alignment process to protect the safety of the product.

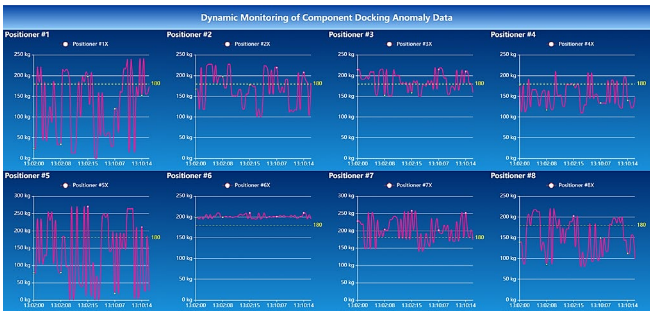

Fig. 6. Visual monitoring of abnormal force values in positioner force sensors

2) Visual Monitoring of Horizontal Measurement Points Data for a Single Sortie

To determine whether the components in a single flight meet the theoretical value requirements during the attitude adjustment and alignment process, it is necessary to calculate the deviation between the actual measurement data in the X/Y/Z direction and the theoretical data for each horizontal measurement point acquired by the laser tracker. At the same time, it is necessary to check in real time that the data from multiple horizontal measurement points are all within tolerance. To visualize the deviation of these horizontal measurement points to guide the attitude adjustment and alignment, it is necessary to present the deviation data of each measurement point in the form of a graph, as shown in Fig. 7. At the same time, to accurately assess whether the final attitude of the part meets the process requirements, symmetry calculations need to be performed based on the data of the horizontal measurement points symmetrically distributed on both sides of the part. The symmetry and deviation need to be presented graphically to assess the final attitude of the part, as shown in Fig. 8.

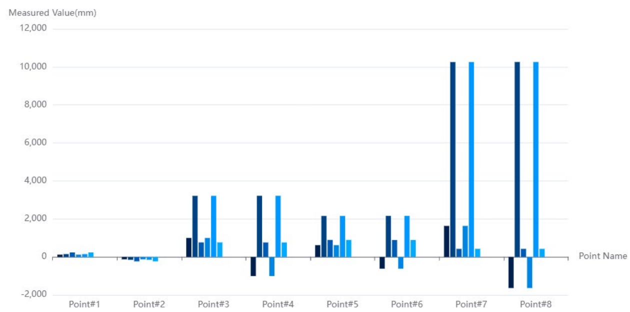

Fig. 7. Visual monitoring of unilateral deviation of horizontal measuring points

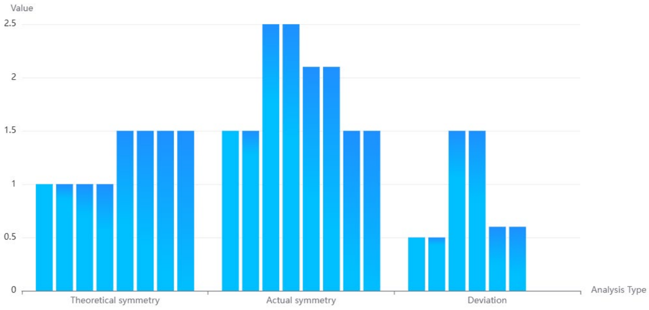

Fig. 8. Visual monitoring of symmetry of horizontal measuring points

3) Visual Monitoring of Horizontal Measuring Points Data for Multiple Sorties

To see the error distribution of the same horizontal measurement points during multiple alignment sorties, the horizontal measurement point data acquired by the laser tracker on the current sortie can be compared. These data include actual measurements in the X/Y/Z directions. These actual measurement data are then combined with the corresponding historical sortie data and displayed in the form of spatial points in a 3D chart. The system can refresh the spatial distribution of multiple measurement points in the 3D chart of the current sortie in real time and compare it with the spatial distribution of the same measurement points in the historical sorties. This makes it easy to evaluate the spatial error distribution range of the horizontal measurement points, as shown in Fig. 9.

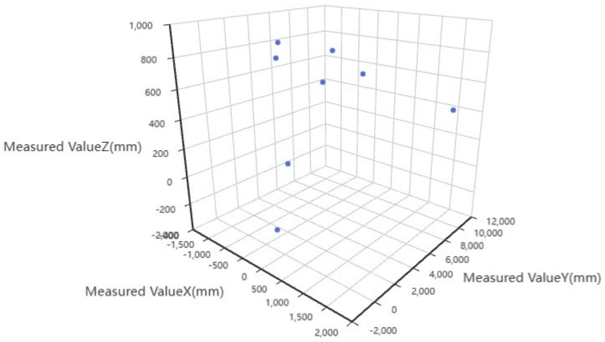

Fig. 9. Visual monitoring of horizontal measuring points data of multiple sorties

C. Real-time Digital Twin Monitoring of the Alignment Process

Digital twin technology provides an efficient remote monitoring and maintenance method for the attitude adjustment and alignment process of aircraft components. By updating data in real-time, the technology enables operators to monitor the motion status of components at any time, regardless of time or place, and take preventive measures before potential quality problems occur.

The system acquires the current position data of the positioner in the PLC device in real time through an efficient data acquisition interface. Transferring this quality data to the Unity3D platform through the timing database interface drives the synchronized motion of the positioner model in the digital twin interface. Through this data-driven approach, a multi-axis cooperative control digital twin model mapping the attitude adjustment and alignment process is established. It is capable of reflecting the actual attitude changes of aircraft components in real time and intuitively, and providing an accurate match between the motion trajectories of airframe components in the virtual environment and the real-world tuning motions, as shown in Fig. 10. This digital twin monitoring approach simplifies component attitude detection based on instrumented measurements and manual observation and significantly improves the efficiency of the alignment and docking process and the safety of the operation.

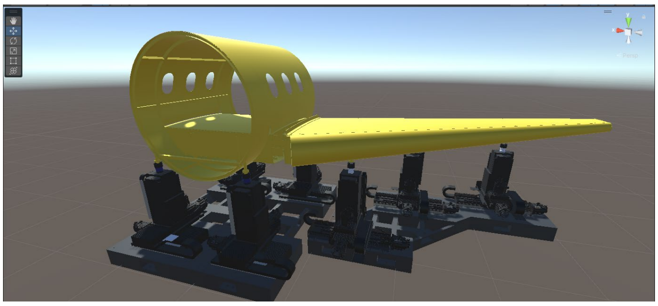

Fig. 10. Unity3D aircraft component alignment digital twin interface

During the entire process from segment alignment to complete machine alignment completion, the system collects and stores quality data from each link. By analyzing evaluating and monitoring these data with real-time twins, it ensures the traceability and controllability of product quality and realizes the automated control of the whole life cycle data of the alignment process. This standardized data monitoring method not only improves the accuracy and efficiency of aircraft assembly but also enables timely detection and resolution of potential problems, thus ensuring product quality and production safety.

V. Conclusion

This study proposes a method to ensure the quality consistency of the aircraft attitude adjustment and alignment process and constructs an automated control system for the whole life cycle quality data. The system collects and stores the whole process quality data based on the process flow, and effectively evaluates the process data according to the process indexes as well as real-time twin monitoring. The core of the system is the integrated monitoring and quality control of different types of process data, which greatly reduces the time required to assess alignment quality. Process personnel use the system to monitor the alignment status in real time and quickly identify potential quality problems through accurate analysis of data, adjusting the alignment strategy promptly to ensure the formation of an efficient and continuous closed-loop quality control system. This whole life cycle quality data control method improves the efficiency and product quality of aircraft assembly and lays the foundation for the intelligence and automation of aircraft manufacturing. In summary, the system proposed in this study not only provides an effective quality control solution for the automated alignment of aviation components but also provides a reference and reference for automated assembly in other fields.

Acknowledgments

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