

Retraction

Retracted: Automatic Data Collecting and Application of the Touch Probing System on the CNC Machine Tool

Mathematical Problems in Engineering

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

- (1) Discrepancies in scope
- (2) Discrepancies in the description of the research reported
- (3) Discrepancies between the availability of data and the research described
- (4) Inappropriate citations
- (5) Incoherent, meaningless and/or irrelevant content included in the article
- (6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

- [1] Z. Tang, X. Jiang, W. Zi, X. Shen, and D. Zhang, "Automatic Data Collecting and Application of the Touch Probing System on the CNC Machine Tool," *Mathematical Problems in Engineering*, vol. 2021, Article ID 6635559, 19 pages, 2021.

Research Article

Automatic Data Collecting and Application of the Touch Probing System on the CNC Machine Tool

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For realizing automatic data collecting of the touch probing system on the CNC machine tool and practicing the application technology of big data from the CNC machining process, a special NC program was developed on the Siemens 840D SL controller to record data with a defined text format, and they were uploaded onto the host computer automatically. With the help of DB management software in the host PC, data obtained were sent into the MES database regularly, and then automatic data collecting of manufacturing process information was realized. With the big data technology, three applications based on big data technology have been listed. They are duo active error detection on the probing system, geometrical accuracy monitoring, and management of the cutting parameter and tool life. Tests of cutting on the platen of an injection molding machine with a PAMA SR3000 floor-type CNC boring-milling machine proved that the new technology achieves its design objectives.

1. Introduction

The “Made in China 2025” strategy was promulgated, clarifying that China will transform from a major manufacturing country to a manufacturing power [1]. According to the implementation guidelines, the machinery manufacturing industry takes the lead in the three aspects of strong foundation, environmental protection, and integration and strives to make breakthroughs in the three directions of talent training, information application, and service-oriented model construction [2]. In recent years, in the communications, transportation, white goods, and other industries, domestically made industrial products have successfully entered the international market, which proves our progress in the field of mid-end CNC machine tools and processing technology [3, 4]. To develop higher-end areas of the manufacturing industry, at the R&D side, we need to do a good job of matching with actual needs to ensure accurate targets. On the application side, we must upgrade equipment and technology; integrate software and hardware technology; and improve technology and management capabilities.

In the published ‘Made in China 2025’ strategy, China clarified that it would change from the big manufacturing country to a strong one. According to the implementation guideline, three aspects of enhancing basic technology, environment protection, and technology combination must take the lead in the machinery industry, and breakthrough in education, information, and building up of service mode are expected. For developing the higher-level manufacturing industry, the exact target of R&D must be set according to the real demand. Upgrade of equipment and process capability, combination of software and hardware, and improvement on technical and general management must be implemented for supporting the application.

An increasingly complex production process is accompanied by huge comprehensive information, covering environment, equipment comprehensive accuracy, tools, technology, efficiency, quality, etc. Disposing of this information with efficient management and technical means will help achieve the ideal high-end CNC machining [5, 6]. In view of actual problems, the research process information is analyzed, and appropriate decisions are made. In the discipline of quality management, this methodology is called

process quality control [7]. The application of digital technology can realize the digitization of the processing process. The application of big data technology can intelligently select and effectively process from massive information, visually display the key points, and guide technology and management to make correct decisions with the most scientific basis [8].

Daily production process is becoming more and more complex that reflects from a big pack of information consisting of environment, equipment accuracy, tools, process, efficiency, quality, and so on. Once the information is efficiently managed with proper technology, the higher-level machining production is achievable. In the study of quality management, process quality control was defined as analyzing and researching process information and making appropriate decisions. With the help of digital technology, detailed process information from production can be collected and stored in a database. Then, the 'big data' technology will study the database for working out some scientific algorithms that can sort out, visualize the essential problems, and provide solutions.

A trigger probe is advanced digital measurement equipment that is commonly used in high-end CNC machine tools and flexible manufacturing systems (FMSs). The native natural digital feature can support the acquisition of data about quality and process from production. Based on software, the probe can measure the point position information on the workpiece in the machine tool and calculate the relevant quality data. Because the measuring environment and conditions are completely the same as manufacturing, the error and deformation caused by the secondary clamping are avoided, and the root cause of the deviation is easy to find out. Compared with the traditional measurement, the measuring process of the trigger probe is controlled by the numerical control system, and the accuracy and efficiency are greatly improved [9]. Many scholars have done research on the measurement and accuracy compensation method of the trigger probe. Zhu [10] developed a measurement software system that automatically selects measurement points, programs, executes, and returns the result data based on the STL model data. Literature studies [11–14] compensated the errors of different contact points on the spherical surface of the trigger probe through a new method and comprehensively improved the theoretical measurement accuracy. It is found in practical applications that most of the measurement errors are based on systemic reasons. The system accuracy of a machine tool could be affected by many factors, and it is difficult to find, trace, and repair immediately, so the method of studying the error of the trigger probe itself is too limited. Ihara [15] thoroughly studied the advantages and disadvantages of the in-machine measurement system, but it lacks practicality for production. Zhou et al. [16] proposed a new in-machine measurement logic based on actual production requirements, but did not introduce how to implement it. In continuous production, in order to reduce quality risks, find errors on time, identify causes, and work out strategy to solve the problem, a fast and effective complete application solution is required, and long-term monitoring technologies and mechanisms are required.

Based on the characteristics and actual needs of CNC machining, this article uses the log recording and process data sharing functions in the Siemens 840D SL CNC system. By compiling a special NC program, the measurement data from the probe are recorded with a standardized format and automatically uploaded onto the host computer. When the data are continuously saved into the MES database through database management software, a simple manufacturing process information collecting system was built up. With the help of big data technology to identify, process data will be filtered, sorted, and analyzed, and then three important technical applications of trigger probes in CNC machining and production are realized:

- (1) Using the probe's ideal reasoning method, the working principle of the trigger probe and the root cause of the error are analyzed, the result-oriented double-effect active probe error monitoring logic is put forward, and the data rules are defined. With the help of standard measuring tools in the machine tool or running a cross-measurement program on the workpiece, the data could be automatically compared, and measurement errors can be found.
- (2) When the probe accuracy is reliable, the principles, manifestations, and failure modes of common errors are sorted out according to machine tool accuracy knowledge, and they are converted into three levels of data rules and mapping logic. By selecting the appropriate measurement data and importing them into the computer, the manifestation and principle of the error can be calculated in reverse according to the conditional formula, which can guide the daily maintenance of equipment.

A three-step mapping logic with formulations can be set up based on the knowledge of machine tools such as error type, behavior, and sample case. When the accuracy of the probe is reliable, once proper measuring result is input into the computer, cases can be processed back through behavior to get the error type which is helpful for daily maintenance work.

- (3) According to the real demand of key process, a set of testing process parameter is obtained based on the reference data from tool manufacture and supplement by orthogonal test method. After screening and processing the data, a mathematical model of dimensional results under different process parameters can be established. The mathematical model contains important data on the quality of the machining process. With the help of visual data technology, process research and tool life management become much easier and can be done actively.

2. Data Acquisition and Digital Manufacturing Information System

2.1. Regulation of the Data Format. A neat data format is the basis for communication. The Siemens 840D SL CNC

provides simple programming in a high-level language that enables basic functions such as NC program jumping, data transformation, and mathematical calculation. According to the exact requirements from a database management system, data obtained in the process can be programmed into the target format. Figure 1 shows the NC program corresponding to the date and time format of a database. Figure 2 shows the execution result.

2.2. Saving and Uploading of Data. Due to the security requirements of the NC system, the NCU is not allowed to be read and written directly from the external device, and direct communication cannot be realized. This is also the reason why SCADA systems require independent communication modules and secondary development. Version 4.7 SP1, Siemens 840D SL CNC systems have added a 'Process Data Share' function, which enables simple NC programming to easily write data segments outward to a fixed text file at a specified address on the LAN, enabling a basic digital communication of machining data at a very low cost. In combination with some other programs in a computer, the digitization of measurement data is possible.

There are five steps to use the 'Process Data Share' function: ① add the authorization of read and write on the host computer for the machine controller through the network; ② add NCU drive paths to the machine to specify the target file to the network, mapping the target folder of the host computer through the network into the NCU configuration; ③ use the EXTOPEN loop to open the external file; ④ use the WRITE loop to write the data segment; and ⑤ use the EXTCLOSE loop to save and close the external file. The data upload is completed. The data upload is completed after it is written into the database by data management system on the host computer.

2.3. Construction of Data Acquisition and Digital Manufacturing Information Systems. Digital manufacturing information system is the system for planning, executing, monitoring, and reviewing of production activities, which are realized with data input, collection, processing, and judging. In today's interconnected world, collecting a large amount of data based on SCADA modules is not difficult, but still expensive. The digital application of the probe requires only a simple information system. There is no reduction in structure to the common solution, just a simplification of the amount of information to be transmitted and the method of collection. The advantage on cost saving is significant.

As shown in Figure 3, the system consists of a CNC machine, information system, and interactive system. By running the NC program cycle, the CNC machine saves the information and data as the text file and transfers it to the buffer area temporarily. Afterward, the buffer area will be read and cleared in the database execution activity. The interactive system is the window for inputting, displaying, maintaining, and managing the information. It could be with different authorizations for reading and writing. Each of them also has a small buffer area for storing and transforming the instruction or data temporarily. The information system consists of a buffer area, a database, and a library of executable instructions for receiving, storing

```

NC/MPF/TEST_STRING
DEF INT ERROR%
DEF INT STR11, STR12, STR13, STR1 : DATE DIGIT%
DEF STRING(30) STR21, STR22, STR23, STR2 : DATE STRING%
DEF INT STR31, STR32, STR33, STR3 : TIME DIGIT%
DEF STRING(30) STR41, STR42, STR43, STR4 : TIME STRING%
%
STR11=2000*SA_YEAR : FORMAT PROCESS%
STR12=100*SA_MONTH%
STR13=100*SA_DAY%
STR21=<<STR11%
STR22=<<STR12%
STR22=SUBSTR(STR22, 1, 2)%
STR23=<<STR13%
STR23=SUBSTR(STR23, 1, 2)%
STR2=STR21<<"/"<<STR22<<"/"<<STR23%
%
STR31=100*SA_HOUR : FORMAT PROCESS%
STR32=100*SA_MINUTE%
STR33=100*SA_SECOND%
STR41=<<STR31%
STR41=SUBSTR(STR41, 1, 2)%
STR42=<<STR32%
STR42=SUBSTR(STR42, 1, 2)%
STR43=<<STR33%
STR43=SUBSTR(STR43, 1, 2)%
STR4=STR41<<":"<<STR42<<":"<<STR43%
%
WRITE(ERROR, "STRING_TEST", <<STR2)%
WRITE(ERROR, "STRING_TEST", <<STR4)%
%
MSG("ERROR CODE IS "<<ERROR)%
%
M00%
M00%

```

FIGURE 1: Time and date program format chart.

```

NC/MPF/STRING_TEST
2019/09/04%
17:39:35%

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FIGURE 2: Time and date program results' chart.

temporarily, and sending the data. It also processes the requested instruction from the interactive system. The host computer in this paper is equivalent to the buffer area, which is used to store temporary data. The interactive system is generally developed autonomously and customized on demand.

3. The Function and Failure Mode of the Probe

3.1. The Structure and Function of the Probing System. A typical probe consists of three parts, the handle, the body, and the stylus, as shown in Figure 4. The tool holder is used to connect different standard CNC machine tool spindles with the probe body. The body is a housing with an industrial-grade environmental protection level. The inside is composed of power supplies, piezoelectric components (or on-off components), analysis circuits, and communications. The stylus is installed on the side facing the worktable and contacts the workpiece to complete the measurement action. The stylus has no special function. It is a rigid slender rod with excellent rigidity and thermal stability. The head of the stylus is a ruby ball head, with high geometrical accuracy, high hardness, and wear resistance which is not easy to deform.

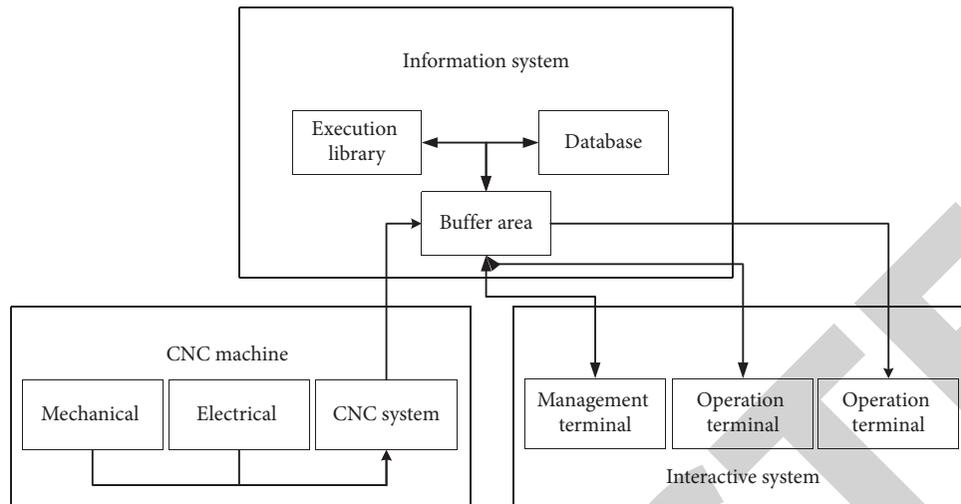


FIGURE 3: Diagram of the digital system.

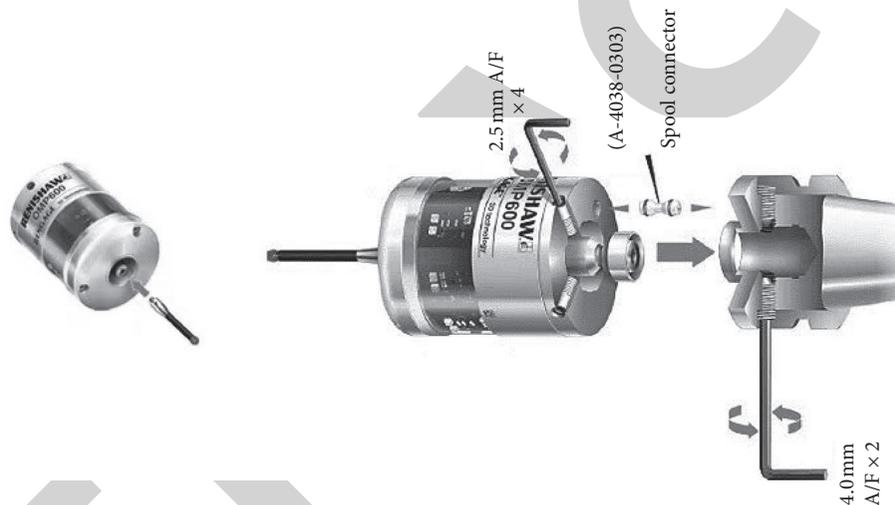


FIGURE 4: Structure diagram of the trigger probe.

On the machine tool, there is a dedicated communication system that is responsible for receiving real-time signals from the measuring head. The probe and the numerical control machine work together to realize the measurement function through program control. After the measurement cycle starts, the probe is activated by the program, and the analysis circuit is turned on. The probe first moves to the safety plane according to the speed and path specified by the program and then approaches the set position on the workpiece in the measurement mode. In the measurement mode, the stylus touches the object, causing the piezoelectric element (or on-off element) to produce displacement (or open circuit), which is sensed by the analysis circuit and then uploaded to the CNC machine tool by the communication circuit. The CNC system of the machine tool immediately records the current position, stops movement, and returns to the safety plane, and a complete typical measurement cycle ends here. The measurement result will be saved into the user variable, and the

corresponding dimension data can be obtained by calculation, and the result beyond the tolerance value will be accompanied by an alarm.

Figure 5 shows the common two-dimensional measurement functions, and Table 1 lists the mathematical formulas they use. The user interface can be customized and developed according to actual needs. The parameters and syntax on different software platforms will be different, but the logic and mathematical principles are always the same.

3.2. Calibration and Failure Mode of Probe Accuracy. The electronic components in the probe body only have the function of determining contact and communication. The accuracy of the probe itself is manually calibrated during the initial installation before using first. As shown in Figure 6, when calibrating, first, the runout of the ruby ball head needs to be measured with a tool presetter or a dial indicator outside the machine. If there is an error of more than 5

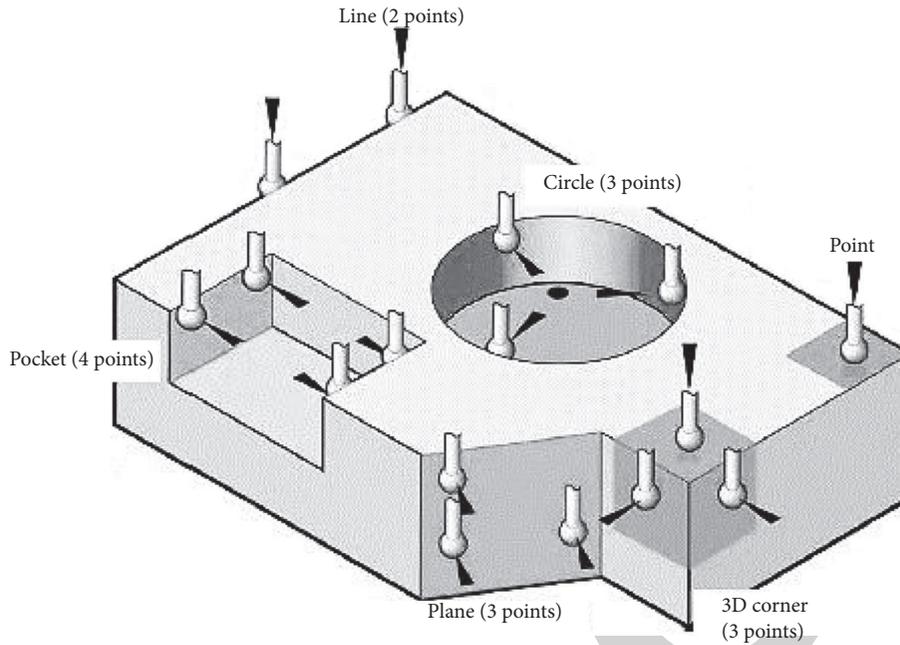


FIGURE 5: Diagram of commonly used measurement functions.

TABLE 1: Mathematical formulas.

Points	Data	Formula	Application
Point1	$P_1(x_1, y_1)$		Position
Point2	$P_1(x_1, y_1), P_2(x_2, y_2)$	$x_m = (x_1 + x_2)/2$ $y_m = (y_1 + y_2)/2$ $P_m(x_m, y_m)$ $l = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$ $k = (y_2 - y_1)/(x_2 - x_1)$ $\theta = \arctan k$	Midpoint Length Slope Angle
Point3	$P_1(x_1, y_1), P_2(x_2, y_2), P_3(x_3, y_3)$	$k_{12} = (y_2 - y_1)/(x_2 - x_1)$ $k_{23} = (y_3 - y_2)/(x_3 - x_2)$ $k_{12} = k_{23}$ $\begin{cases} (x_1 - a)^2 + (y_1 - b)^2 = R^2 \\ (x_2 - a)^2 + (y_2 - b)^2 = R^2 \\ (x_3 - a)^2 + (y_3 - b)^2 = R^2 \end{cases}$ $O(a, b); R$	Collinear Center
Point4	$P_1(x_1, y_1), P_2(x_2, y_2), P_3(x_3, y_3), P_4(x_4, y_4)$	$x_{m13} = (x_1 + x_3)/2$ $y_{m13} = (y_1 + y_3)/2$ $x_{m24} = (x_2 + x_4)/2$ $y_{m24} = (y_2 + y_4)/2$ $l_{13} = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$ $l_{24} = \sqrt{(x_4 - x_2)^2 + (y_4 - y_2)^2}$ $\begin{cases} (x_1 - a)^2 + (y_1 - b)^2 = R^2 \\ (x_2 - a)^2 + (y_2 - b)^2 = R^2 \\ (x_3 - a)^2 + (y_3 - b)^2 = R^2 \end{cases}$ $O_{123}(a_{123}, b_{123}); R_{123}$ $O_{124}(a_{124}, b_{124}); R_{124}$ $O_{134}(a_{134}, b_{134}); R_{134}$ $O_{234}(a_{234}, b_{234}); R_{234}$	Radius Length Center radius



FIGURE 6: Probe error pattern diagram.

microns, the positioning bolt is adjusted to improve the runout to the target value. After the probe is installed in the machine, the calibration program is run to measure the ring gage to complete the parameter setting of the software compensation. For some applications that need to measure curved surfaces, development of more advanced three-dimensional compensation logic is needed [11–14].

The structure of the probe can theoretically maintain high accuracy for a long time, but some external factors in practical applications will make the probe accuracy slow or suddenly fail. Typical failure mode one is the accumulation of dirt on the taper hole of the machine tool spindle, and geometric and positioning errors appear after the installation of the taper shank of the probe. Typical failure mode two is that the processing environment has caused contamination on the ruby ball head of the probe, which directly caused the deviation of the measurement result. Regularly checking the accuracy of the probe can effectively reduce quality risks. The key is to find a convenient and effective method.

Both theory and practice tell us that, in two-dimensional measurement, the three-dimensional probe has only one failure mode, and it can swing with the rotation of the spindle angle, as shown in Figure 7, in micrometers.

4. Double-Effect Active Probe Error Monitoring

4.1. Manifestation of the 3D Probe. The 3D probe is the most commonly used type of probe. We set the 3D probe to the sphere center mode and took the deviation on 0° as the reference value for studying the actual influence from the offset-type deviation. By the ideal reasoning method, failure modes of commonly used measuring functions had been worked out.

Figure 8 shows the failure mode of a single-point measurement error. The measurement result is directly opposite to the direction of the probe error.

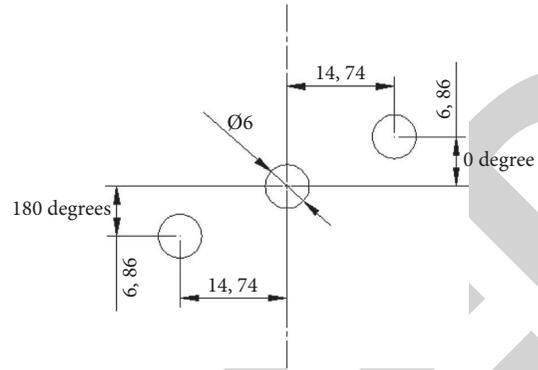


FIGURE 7: Error pattern diagram of the three-dimensional probe.

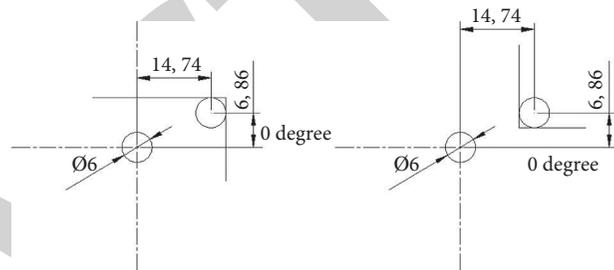


FIGURE 8: Single-point error mode diagram.

Figure 9 shows the failure form of the two-point measurement error. The result of the midpoint position is also directly opposite to the error direction, but due to the calculation principle, the application of measuring length, slope, and angle is not affected.

Figure 10 shows the failure mode of the three-point measurement error. The measured slope and radius are not affected, but the result of the center position is directly opposite to the error direction.

The failure form of the four-point measurement error is a combination of two-point measurement and three-point measurement. It is not affected when measuring dimensions such as groove width or radius, but the position results of the midpoint and the center of the circle are directly opposite to the error direction.

4.2. Monoprobe and Its Error Manifestation. The early electronic technology was not advanced enough and could only manufacture probes for unidirectional workpiece measurement. When the measuring direction changes, the spindle of the machine tool needs to be rotated for adapting. Later, with the development and application of probes, in order to measure the workpieces in different shapes, many special styles were derived, as shown in Figure 11. In today's Siemens machine tool system, monoprobe and its cycles remain, which greatly expands the possibilities of probe applications.

We used the same method to reason out the error manifestation of the monoprobe and obtained another set of results.

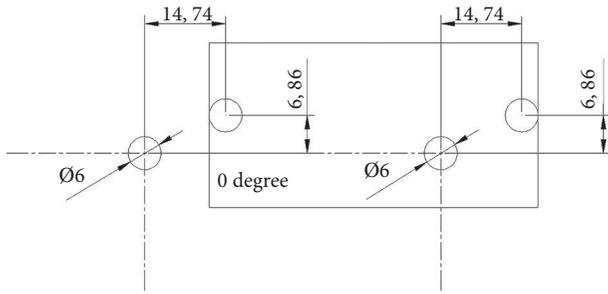


FIGURE 9: Two-point error pattern diagram.

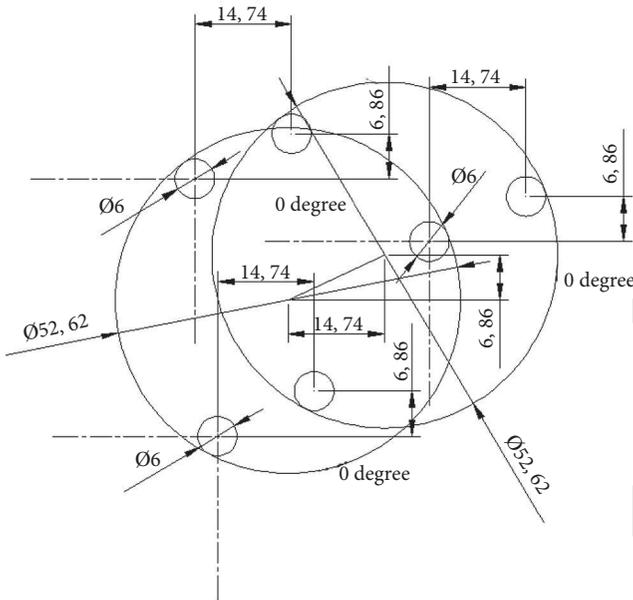


FIGURE 10: Three-point error pattern diagram.

Loc.	Type	Tool name	S	New tool - special tools	Type	Identifier	Tool position
11	DRILL	DRILL 10		780	-	Slotting saw	
12	PREDRILL	PREDRILL 30		710	-	3D probe	
13	DRILL_Tool	DRILL_Tool		711	-	Edge finder	
14	THREAD CUTTER	THREAD CUTTER M10		712	-	Mono probe	
15	THREAD CUTTER	THREAD CUTTER M10		713	-	L probe	
16				714	-	Star probe	
17				725	-	Calibrating tool	
18				730	-	Stop	
19				900	-	Auxiliary tools	
20							
21							
22							
23							
24							
25							
26							
27							

FIGURE 11: Probe mode setting diagram.

Figure 12 shows the failure mode of the single-point measurement error; the measurement result is directly opposite to the direction of the probe error.

Figure 13 shows the failure mode of the two-point measurement error. When measuring the midpoint position, due to the 180-degree rotation of the monoprobe on the

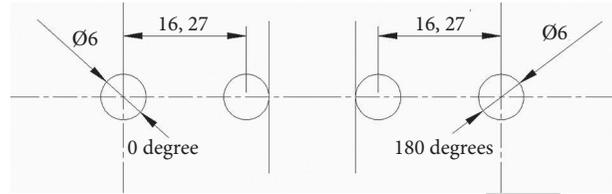


FIGURE 12: Single-point error mode diagram of the monoprobe.

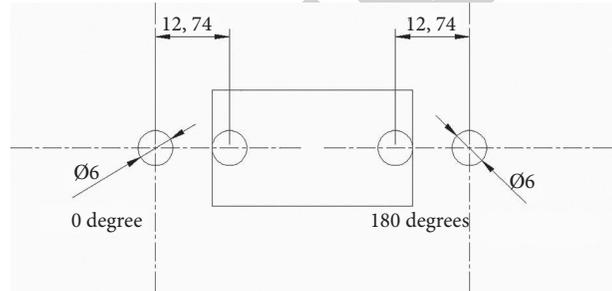


FIGURE 13: Two-point error mode diagram of the unidirectional probe.

spindle, the two deviations of the same magnitude but opposite directions counteracted, and the result was not affected. When measuring the length, the two errors are superimposed due to the 180-degree rotation of the spindle, and the result will be larger or smaller depending on the direction of the error. According to the calculation, the measurement results of slope and angle are not affected.

Figure 14 shows the failure mode of the three-point measurement error. The results of measuring the slope and the position of the center of the circle are not affected, but the result of the radius will become larger or smaller depending on the direction of errors.

The failure mode of the four-point measurement error is still a combination of two-point measurement and three-point measurement. The results of positions such as the midpoint and the center of the circle are not affected, but for dimensions such as groove width or radius, the results will become larger or smaller depending on the direction of the error.

4.3. Two Methods of Double-Effect Error Recognition. A monoprobe has the same specification as a 3D probe except the need of spindle orientation. The 3D probe can work in two modes, respectively. Based on the 840D SL numerical control system, the 3D probe is allowed to be used with two modes, respectively. We have compiled the characteristics of measurement errors from each mode as shown in Table 2. Through reasoning, we obtained a complementary logic, that is, using two probe modes on one 3D probe that can eliminate or monitor probe errors. Furthermore, in Table 2, the complementary items of each measurement function are marked in different colors.

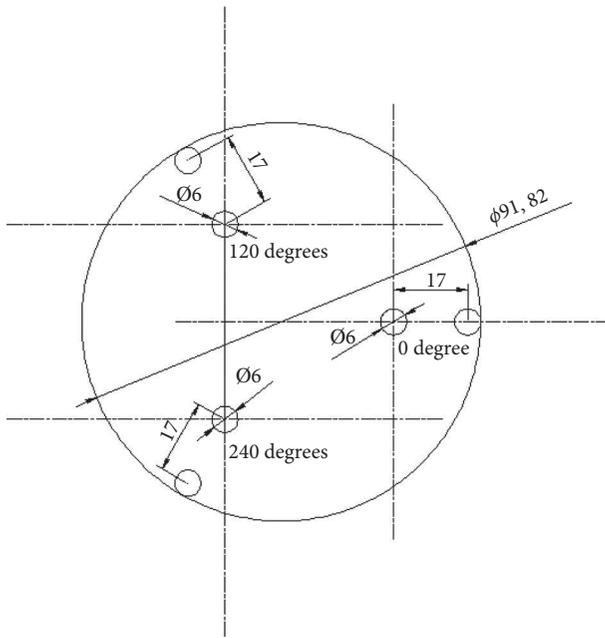


FIGURE 14: Three-point error mode diagram of the monoprobe.

Double-effect error recognition means that the error can be collaboratively judged based on the real-time measurement results or long-term monitoring data analysis. According to the principle of the probe error, we designed two methods to identify error occurrence. Both methods use the important conclusions in Table 2, which are simple in logic and with practical significance. The first method focuses on theoretical application and is suitable for small species and large-scale processing. As shown in Figure 15, when the machine tool table has enough free space, we fix a high-precision ring gauge with antirust performance on one side of the table and use the probe to measure the position of the three linear axes of the machine tool, X, Y, and Z. Comparing the real-time measurement result with the standard value saved during the acceptance of the machine tool, it can be judged whether the positioning accuracy of the machine tool has deviated. The second method is to verify the accuracy of the machine tool with the finishing features of the part itself. As shown in Figure 16, one can choose the position of the workpiece surface or plane or fine boring, and more consideration is given to the production characteristics of multivariety and small-batch parts, but the application technology capabilities of the probe are higher.

4.4. Establishment of the Error Recognition Logic. According to the two conclusions mentioned above about the principle of the probe error and inference method of the error source on the machine tool, we have, respectively, formulated the program logic of the two methods, as shown in Figures 17 and 18. Based on actual production requirements, both logics have set up two modes for normal processing or monitoring. During continuous

production or when it is inconvenient to stop and adjust, the normal processing mode is used to perform the measurement with maximum efficiency, or the monitoring mode is used to ensure that the probe is always in the normal accuracy state.

4.5. Establishment of the Data Output Format. In order to achieve continuous data recording, we need to define the standard format of the measurement log, which is a necessary tool for the host computer to collect data. According to actual needs, we have defined a data record table, as shown in Table 3. After setting a proper update frequency for the data, a simple API was realized. Information is collected and recorded to the database at a higher frequency on the host computer, and the data collection is completed.

According to the data format requirements in Table 3, each group of data in the output form has 9 rows, and each row consists of 4 groups of characters and 3 groups of floating-point numbers, which are convenient for later maintenance and expansion. According to the first measurement logic, we installed a ring gauge on the machine tool table. In the factory setting, the diameter of the ring gauge is 80.393 mm, and the distance between the center of the ring gauge and the mechanical origin of the machine tool is 300 mm in both X-axis and Y-axis directions. This set of data will appear in the first row of data. Using measurement cycle 977, the result parameters are diameter_OVR [4], center X-axis position_OVR [5], and center Y-axis position_OVR [6]. This set of data is stored in the second, third, and fifth rows. In order to test the program, three result parameters are preassigned, and three production information data are also predefined.

4.6. Output and Upload of Probe Measurement Results. The NC program used to output the specification log is very long. Figures 19 and 20 show the whole paragraphs. Figure 21 shows the result of executing the complete output program, and the format is as expected. The text interval adopts tabs, which can be read by database management software of the host computer. If people use VB or C-language to develop a program that automatically writes data to the database, the same effect can be achieved.

5. Machine Tool Geometric Accuracy Monitoring

5.1. Machine Tool Accuracy System. The precision system of CNC machine tools is realized with both mechanical hardware and NC control software. Hardware such as machine bed is responsible for geometric-related accuracy. Transmission system and software are responsible for positioning accuracy, which is possible to compensate the geometric deviation dynamically a little. Different types of machine tools are different in structure, but the principle of precision is the same. Figure 22 is a structural

TABLE 2: Error characteristics' table under two probe modes.

Point	Model	Position (center)	Midpoint	Length	Slope	Angle	Radius
Point1	Unidirectional	N					
	Multidirectional	N					
Point2	Unidirectional	Y		N	Y	Y	
	Multidirectional	N		Y	Y	Y	
Point3	Unidirectional	Y			Y	Y	N
	Multidirectional	N			Y	Y	Y
Point4	Unidirectional	Y	Y	N			N
	Multidirectional	N	N	Y			Y



FIGURE 15: Measuring X-, Z-, and Y-axis position diagram.



FIGURE 16: Measuring the workpiece itself.

diagram of a typical floor boring and milling machine, and the research in this section is mainly carried out around it.

Cutting and online measuring in a CNC machine tool are based on the same accuracy system, so the study of measurement errors must start with the machine tool accuracy system. As the principle basis of this research,

Figure 23 lists the uncertainty of machine tool operation with classification.

5.2. *Evaluation Method of Machine Tool Accuracy.* The accuracy of the machine tool consists of three parts: positioning, geometry, and dynamics. Positioning accuracy describes the accuracy of the machine tool moving to a predetermined position on each axis, which is determined by the manufacturing and assembly accuracy of the transmission system. It uses positioning deviation Pa , reverse error U , positioning distribution domain Ps , and positioning uncertainty P , the 4 metrics to describe. The industry mostly adopts the German VDI 3441 [17] standard, which is the most rigorous and reliable compared to Japanese and American standards. The geometric accuracy refers to the state of the geometrical condition referring to each axis direction, which is determined by the manufacturing and assembly accuracy of the machine bed components. According to single-axis and multi-axis correlation, it can be evaluated with straightness, perpendicularity, parallelism, circular runout, and other items. The geometric accuracy is described in detail in the ISO 230-1: 2012 [18] standard, and GB/T 17421.1-1998 [19] is equivalent. Dynamic accuracy is a comprehensive manifestation of machine tool motion performance and stability based on positioning accuracy and geometric accuracy. GB/T 17421.3-2009 [20] specifies the thermal stability evaluation method, GB/T 17421.4-2016 [21] specifies the profile evaluation method, GB/T 17421.5-2015 [22] specifies the noise evaluation method, and GB/T 16768-1997 [23] specifies the vibration evaluation method. Many factors in these standards comprehensively constitute the dynamic accuracy of the machine tool.

After the machine is set up and handed over, the manufacturer will provide a complete acceptance accuracy report. In daily maintenance, the actual accuracy of the machine tool is compared with the acceptance accuracy. If the two are different, the machine should be stopped, and adjustment is needed to avoid quality accidents.

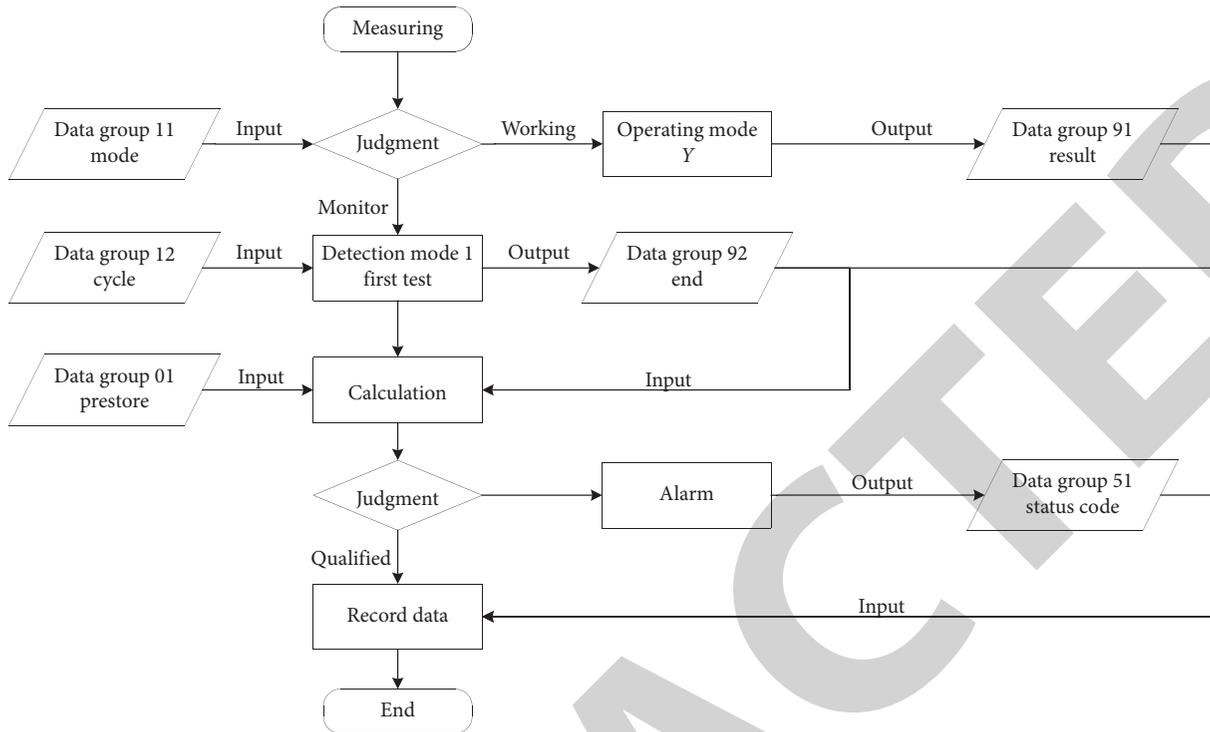


FIGURE 17: The first measurement logic diagram.

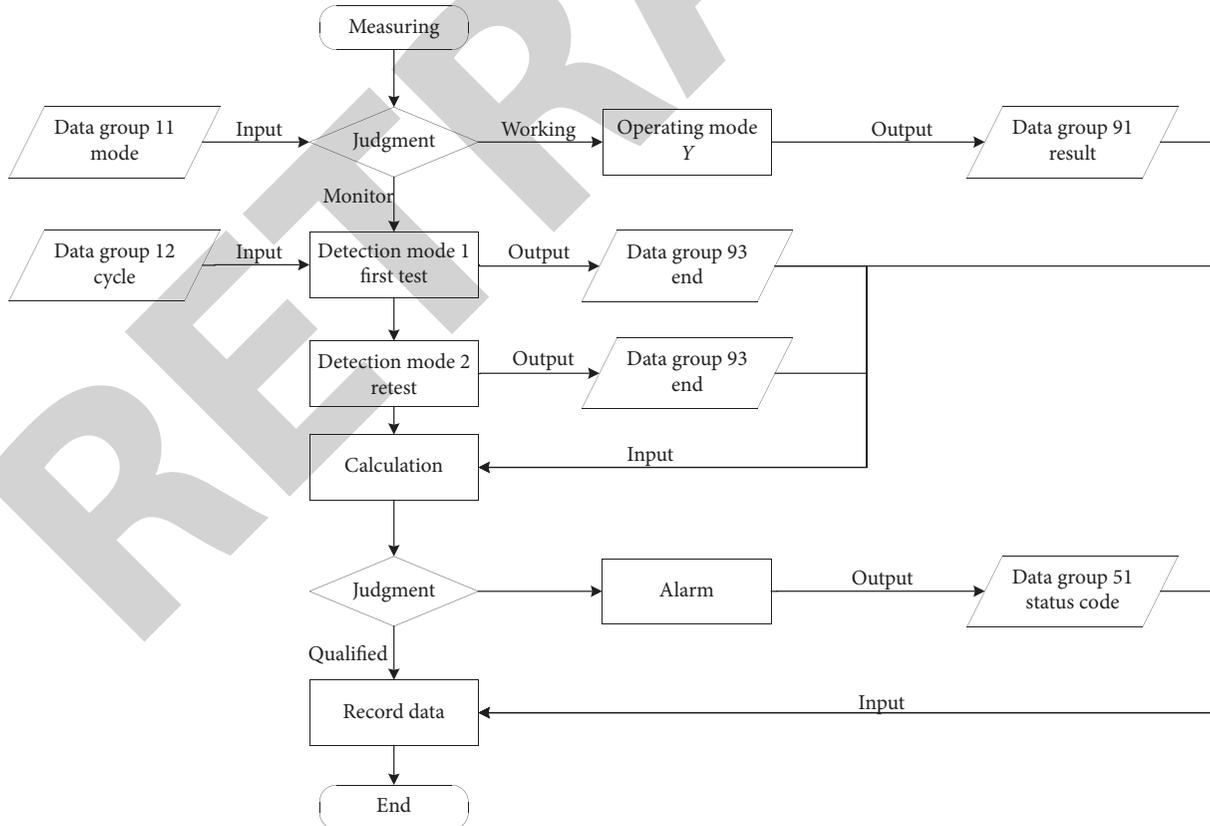


FIGURE 18: The second measurement logic diagram.

TABLE 3: Measurement data format.

Project Character	Description Character	Data				
		Double	Double	Double	Character	Character
Record	order	order	Components	Program	Date	Time
Data01	prestore					
Data11	mode					
Data12	cycle					
Data91	result					
Data92	result					
Data93	result					
Data94	result					
Data51	status					

```

NC/MPF/TEST_NC_9 22
DEF INT ERROR ; CYCLE NEED
|
|
DEF INT STR11, STR12, STR13, STR1 ; DATE DIGIT
DEF STRING(30) STR21, STR22, STR23, STR2 ; DATE STRING
DEF INT STR31, STR32, STR33, STR3 ; TIME DIGIT
DEF STRING(30) STR41, STR42, STR43, STR4 ; TIME SPRING
|
DEF STRING(30) ITEM, DSC, DATE, TIME ; DEFINE ROU
DEF REAL RES1, RES2, RES3 ; DEFINE ROU
|
DEF INT ORDER, PRT, PGM ; EXTERNAL DATA
ORDER=11111111 ; EXTERNAL DATA
PRT=22222222 ; EXTERNAL DATA
PGM=33333333 ; EXTERNAL DATA
_OVR(4)=300.022 ; INTERNAL DATA
_OVR(5)=299.997 ; INTERNAL DATA
_OVR(6)=80.388 ; INTERNAL DATA
|
|
|-----|
STR11=2000+SA_YEAR ; FORMAT PROCESS
STR12=100+SA_MONTH ; DATE
STR13=100+SA_DAY
STR21=<<STR11
STR22=<<STR12
STR22=SUBSTR(STR22, 1, 2)
STR23=<<STR13
STR23=SUBSTR(STR23, 1, 2)
DATE=STR21<<"/"<<STR22<<"/"<<STR23
|
STR31=100+SA_HOUR ; FORMAT PROCESS
STR32=100+SA_MINUTE ; TIME
STR33=100+SA_SECOND
STR41=<<STR31
STR41=SUBSTR(STR41, 1, 2)
STR42=<<STR32
STR42=SUBSTR(STR42, 1, 2)
STR43=<<STR33
STR43=SUBSTR(STR43, 1, 2)
TIME=STR41<<"/"<<STR42<<"/"<<STR43
|
|
|-----|
; PRINT OUT THE HEADER ; LINE 1
ITEM="RECORD"
DSC="ORDER"
RES1=ORDER
RES2=PRT
RES3=PGM
WRITE(ERROR, "LOGBOOK", <<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
|
; PRINT OUT THE PRESET ; LINE 2
ITEM="DATA01"
DSC="PRESET"
RES1=300 ; X POSITION
RES2=300 ; Y POSITION
RES3=80.393 ; DIAMETER
WRITE(ERROR, "LOGBOOK", <<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
|

```

FIGURE 19: Output program diagram 1.

5.3. Composition of the Measurement System. The current measurement technology provides a mature solution for high-precision measurement of the real-time position of the moving parts of a machine tool, while the detection of geometric accuracy still uses traditional methods.

The positioning systems of high-precision CNC machine tools adopt closed-loop control, as shown in Figure 24, that is, the rotary encoder built into the servo motor at the drive end, together with the linear encoder on the linear axis of the

action end, or the rotary encoder on the terminal rotary axis. The system can also set up a compensation according to the environment change based on the thermal deformation principle and results from laser measurement that further optimize the positioning accuracy of the action end. Once the machine tool is turned on, it is controlled by the closed-loop system at any time, and the positioning accuracy is guaranteed.

The bed of a large machine tool mostly adopts a split structure, and the geometric accuracy is distributed and adjusted after installation. The small machine tool adopts an integral bed, and the geometric accuracy is adjusted during the assembly and usually does not need to be adjusted again after transportation and hoisting. All adjustment works are done by humans with tools, with the help of measuring tools or instruments such as level gauges and square rulers. There is no complete or automated solution.

As long as the machine tool is running normally, it is based on the same measurement system. Usually, systematic deviation will be copied onto the measurement, which leads to the efficacy loss of online measuring. Only by using third-party detection methods such as CMM can we find that the errors have different manifestations.

5.4. Error Source Inference Method Based on Big Data Technology. The accuracy principle of the machine tool is analyzed, all the error sources are sorted in Table 4, the respective manifestations and consequences are studied, and they are associated with typical examples. The application requirement from production is using error results to speculate or judge the cause and give reference for the repair work. A certain number of inspection reports are collected, big data technology is used to sort and analyze valid data, an error pattern is formed with the typical examples in Table 4, reversing the direction of reasoning, and eliminating the interference items, and then the true source of error could be found. Figure 25 is the report of the positioning accuracy from the laser interferometer. The line graph is an important basis for filtering interference factors in reasoning.

Figure 26 shows the mapping relationship between the test report data group and the error source, and the logical sequence is the difficulty of adjustment. The purpose of processing data is to establish a mathematical model to determine the error mode. Because different machine tools

```

NC/MPF/TEST_NC_9 67
-----
;PRINT OUT THE MODE ;LINE 3
ITEM="DATA11"
DSC="MODE"
RES1=1 ;0==WORK 1==MEASURE
RES2=0
RES3=0
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
;PRINT OUT THE CYCLE ;LINE 4
ITEM="DATA12"
DSC="CYCLE"
RES1=977 ;HOLE 4 POINTS
RES2=0
RES3=0
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
;PRINT OUT THE RESULT ;LINE 5
ITEM="DATA91"
DSC="RESULT"
RES1=0 ;RESULT
RES2=0
RES3=0
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
;PRINT OUT THE RESULT ;LINE 6
ITEM="DATA92"
DSC="RESULT"
RES1=_OVR[4] ;RESULT
RES2=_OVR[5]
RES3=_OVR[6]
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
;PRINT OUT THE RESULT ;LINE 7
ITEM="DATA93"
DSC="RESULT"
RES1=0 ;RESULT
RES2=0
RES3=0
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
;PRINT OUT THE RESULT ;LINE 8
ITEM="DATA94"
DSC="RESULT"
RES1=0 ;RESULT
RES2=0
RES3=0
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
;PRINT OUT THE JUDGE ;LINE 9
ITEM="DATA51"
DSC="JUDGE"
RES1=1 ;JUDGE
RES2=0
RES3=0
WRITE(ERROR,"LOGBOOK",<<ITEM<<" "<<DSC<<" "<<RES1<<" "<<RES2<<"
"<<RES3<<" "<<DATE<<" "<<TIME)
;
-----
MSG("ERROR CODE IS "<<ERROR)
I100
I130
    
```

FIGURE 20: Output program diagram 2.

```

NC/MPF/LOGBOOK 1
RECORD ORDER 11111111 22222222 33333333 2019/09/04 19:14:45
DATA01 PRESET 300 300 00 393 2019/09/04 19:14:45
DATA11 MODE 1 0 0 2019/09/04 19:14:45
DATA12 CYCLE 977 0 0 2019/09/04 19:14:45
DATA91 RESULT 0 0 0 2019/09/04 19:14:45
DATA92 RESULT 300 022 299 997 00 388 2019/09/04 19:14:45
DATA93 RESULT 0 0 0 2019/09/04 19:14:45
DATA94 RESULT 0 0 0 2019/09/04 19:14:45
DATA51 JUDGE 1 0 0 2019/09/04 19:14:45
    
```

FIGURE 21: The result of the complete output program.

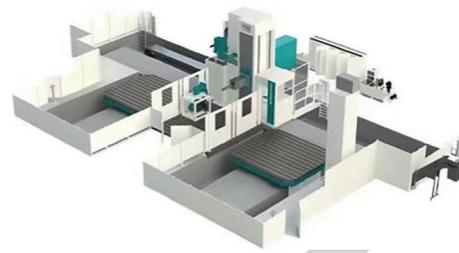


FIGURE 22: The structure of a typical floor boring and milling machine.

and parts vary a lot, the examples listed in Table 4 are just limited. Other factors only include external factors and cannot be changed by modifying the machine settings, so they are prioritized in reasoning. Combined with the positioning accuracy report, determine whether it is a single positioning, geometric, or dynamic accuracy or a complex problem of multiple factors. For large machine tools, the workload of stopping to adjust the geometric accuracy is very large, and the probability of occurrence is small, so the first two inferences are given priority. This reasoning process is completed by big data technology, which can quickly and efficiently draw conclusions and provide a basis for accuracy analysis.

6. Cutting Parameter and Tool Life Management

6.1. *Research for Process Quality.* The tool's process parameters and life management is the most basic category of CNC machining technology management. Process research refers to finding the optimal cutting process, learning the patterns of tool wear and machining dimensional changes, and developing countermeasures to achieve stable process quality.

Cutting parameter and tool life management are the two most important basic technologies for machining. By research on the cutting process, we gain the experience on tool wear and its influence on the target dimension and are able to create the strategy for getting stable process quality.

Process quality is generally composed with 3 sections: the early goal is to prepare and prevent; the medium-term function is to plan, execute, monitor, and adjust; and the later stage is about recording and tracing based on the requirement of the quality management system. Good process quality directly improves the operation performance of the plant. The fundamental purpose of using probes is to improve process quality through digital technology.

6.2. *Preparation before Utilizing the Probe in a Finish Boring Process.* Finish boring for a big diameter hole is the most critical machining process in manufacturing of hydraulic machine. As shown in Figure 27, 4 holes with diameter 270 H7 on a fixing platen for a big tonnage hydraulic machine need to be made, with 350 depth and Ra 1.6 roughness requirement. The hole on the left side is usually finished using the reverse boring process. We have added a process

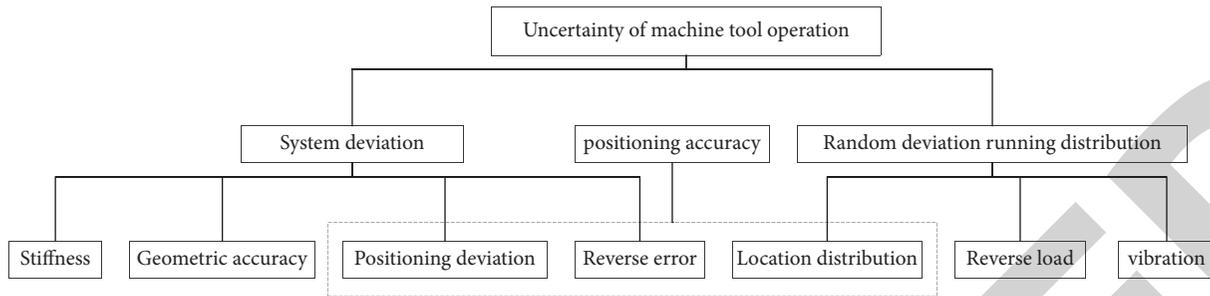


FIGURE 23: Uncertainty of machine tool operation.

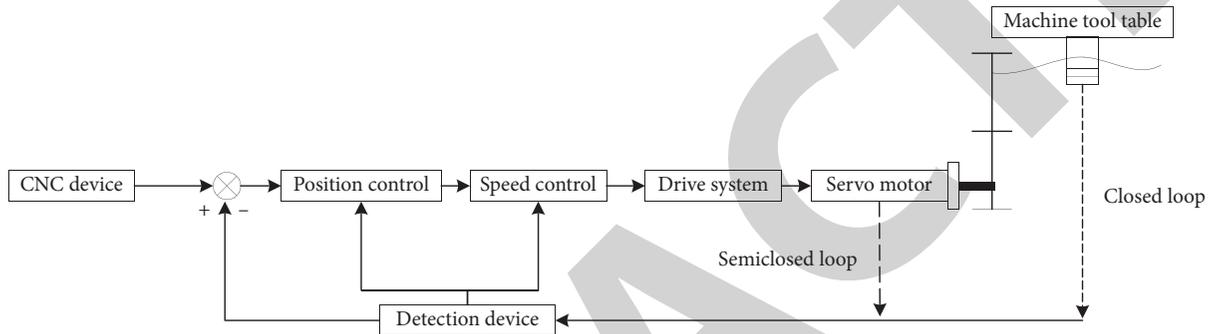


FIGURE 24: Full closed-loop control system diagram of the CNC machine tool.

slot at the bottom of the left hole for tool entry, which allows the machining to be completed in one direction with a single fine boring tool.

Finish boring for a big-diameter hole is the most critical machining process in the manufacturing of hydraulic machines. As shown in Figure 27, 4 holes with diameter 270H7 on a fixing platen for a big-tonnage hydraulic machine need to be made, with 350 depth and Ra 1.6 roughness requirement.

The Sandvik fine boring inserts were selected, and the recommended cutting parameters are shown in Figure 28. The workpiece material is pearlitic ductile cast iron, 0.12 mm per revolution feed, 0.25 mm semifinishing allowance, and 180 m/min cutting line speed were selected for process calculations, and the process is shown in Table 5.

Using the process parameters obtained in Table 5 as reference values, we control the feed rate, vary the rotational speed, and conduct an orthogonal test study of cutting parameters and tool wear, with the planned test parameters listed in Table 6.

6.3. Process Quality Data Acquisition. The principle of finish boring is enlarging the hole diameter, and the wear of the tool tip is directly reflected in a reduction in the size of the machined diameter. In order to study the pattern of cutting speed and tool wear, five parts were machined on a PAMA floor-type CNC milling-boring machine with five sets of cutting parameters, for a total of 20 holes. For every two holes machined, an insert was rotated or replaced with a new

cutting edge. After each insert change, a test cut is made to ensure that the machining dimensions are as consistent as possible.

In the boring process, cutting depth increased together with the growing cutting length accompanying a helical tool path. When the performance of the cutting edge is good, the roughness is fine, and the diameter decreases slowly with the linear tool wear. So, diameter on an exact depth reflects the tool wear after a certain cutting length.

According to the actual shape of the hole, four process-representative, even-numbered points from the depth octet were selected for measurement. The tests yielded ten valid datasets, as shown in Table 7, with cutting speeds decreasing from top to bottom by part group.

6.4. Data Processing and Analysis. After the data are retrieved, the first value of each set of data is aligned. Clustered bar charts and 3D bar charts are produced, as shown in Figures 29 and 30. The clustered bar chart makes the data visible in one dimension, which is equivalent to using the control variable method. The data in the 3D bar chart are visible in two dimensions, which can be used to compare more relevant conditions. With the graphical display of the results, it is easy to observe the effect of an increase in cutting speed on part accuracy. Tool suppliers recommend inserts with a machining life of 20 to 30 minutes, or about 5,000 meters. Tests have confirmed that the recommendations are accurate and valid. Inserts that exceed the recommended service life increase vibration during machining, affect accuracy, and reduce surface roughness. The faster the cutting speed a tool uses, the faster it

TABLE 4: Manifestations of error.

Principle	Subitem	Manifestations and consequences	Typical examples/models
Bed factors	Rigidity	Deformation of the bed under load	Localized radial deviation of shape accuracy; localized divergence of position accuracy Not enough allowance after roughing for finishing; poor geometric or position accuracy in a particular machining area of the machine tool
	Geometric precision	Bed geometry deviations	Shape accuracy deviation; geometric deviation in position accuracy Persistently poor geometrical accuracy in perpendicularity, parallelism, flatness, etc.; the position of the pore system deviates continuously from the geometrical pattern
Drive, lubrication, and CNC factors	Positioning deviation	Large absolute deviations in unidirectional positioning of the bed	Offset and stable position accuracy Consistently and consistent poor position accuracy in the serial production on exact fixture
	Reverse error	Large positioning deviation of the bed's reciprocating motion	Offset and regular position accuracy Exceedingly poor accuracy in rows or columns with toolpaths in opposite directions during complete column feature machining; poor positional accuracy and visible tool marks on curved surfaces in machine tools with frequent axis changes
	Position distribution	High repetitive positioning deviation for unidirectional bed movement	Offset and instable position accuracy There are no individual instances of failure, which are usually superimposed on the positioning bias factor in the results
Other factors	Payload	Changes in the geometric accuracy of the machine under load	Shape accuracy deviation; geometric deviation in position accuracy After loading, the geometrical accuracy of perpendicularity, parallelism, flatness, etc., is consistently out of whack; after loading, the position of the pore system continues to deviate in a geometrical pattern
	Vibration	Resonance of machine tools in specific operating conditions	Unusual vibration noise; poor surface quality of machined parts The surface roughness is extremely poor, but the dimensions are acceptable; the machined surface has a regular knife pattern
	Temperature fields	Deformation of bed components or workpieces with temperature rise	Offset and instable position accuracy Difference in temperature between day and night in nontemperature-controlled workshops and variation in overall accuracy; parts with particularly long machining times and variations in local accuracy

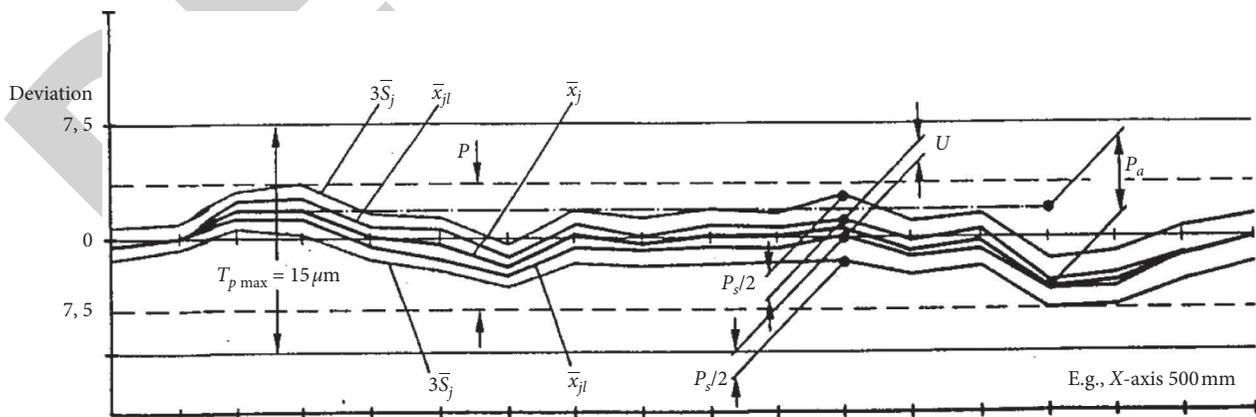


FIGURE 25: Laser interferometer report.

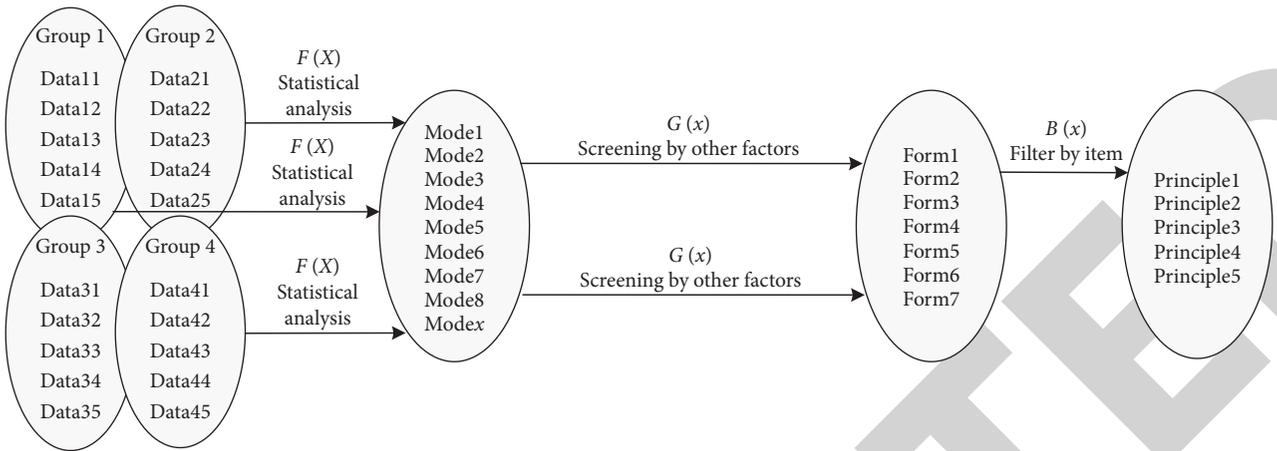


FIGURE 26: Inference map.

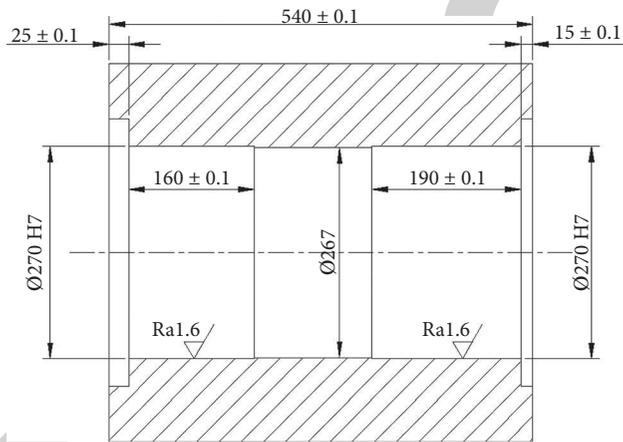


FIGURE 27: Injection molding machine template fine boring diagram.



FIGURE 28: Reference cutting data chart for boring inserts.

TABLE 5: Fine-boring process parameter table.

Name	Symbol	Size	Unit	Formula	Result
Processing diameter	D	270	mm		
Hole circumference	C		mm	$C = \pi * D$	848.23
Feed rate	f_n	0.12	mm		
Depth 1	h_1	190	mm		
Depth 2	h_2	160	mm		
Cutting length	L		m	$L = ((h_1 + h_2) * C / f_n * 100)$	2474.00
Cutting speed	v_c	180	m/min		
Rotation speed	n		rpm	$n = (1000 * v_c / D * \pi)$	212
Time	t		m	$t = (L / v_c)$	13.74

TABLE 6: Fine-boring process test parameter table.

Parameter	Chip speed	Rotation speed	Time	Total time
20%	216	254	11.45	45.80
10%	198	233	12.49	49.96
Recommended value	180	212	13.74	54.96
-10%	162	191	15.11	60.46
-20%	144	170	16.49	65.95

TABLE 7: Fine-boring measurement data sheets.

Part	Hole	Depth1 43.5	Depth2 131.25	Depth3 218.75	Depth4 306.25
1	1	270.031	270.028	270.027	270.024
	2	270.021	270.018	270.014	270.011
	3	270.027	270.024	270.023	270.021
	4	270.019	270.016	270.014	270.009
2	1	270.033	270.029	270.028	270.026
	2	270.023	270.022	270.019	270.016
	3	270.029	270.027	270.026	270.023
	4	270.022	270.019	270.017	270.014
3	1	270.028	270.025	270.024	270.022
	2	270.021	270.019	270.018	270.015
	3	270.035	270.034	270.032	270.029
	4	270.028	270.026	270.023	270.021
4	1	270.033	270.031	270.028	270.027
	2	270.025	270.023	270.020	270.019
	3	270.028	270.025	270.024	270.022
	4	270.021	270.019	270.016	270.014
5	1	270.035	270.033	270.032	270.030
	2	270.027	270.025	270.024	270.022
	3	270.029	270.028	270.025	270.024
	4	270.022	270.019	270.018	270.016

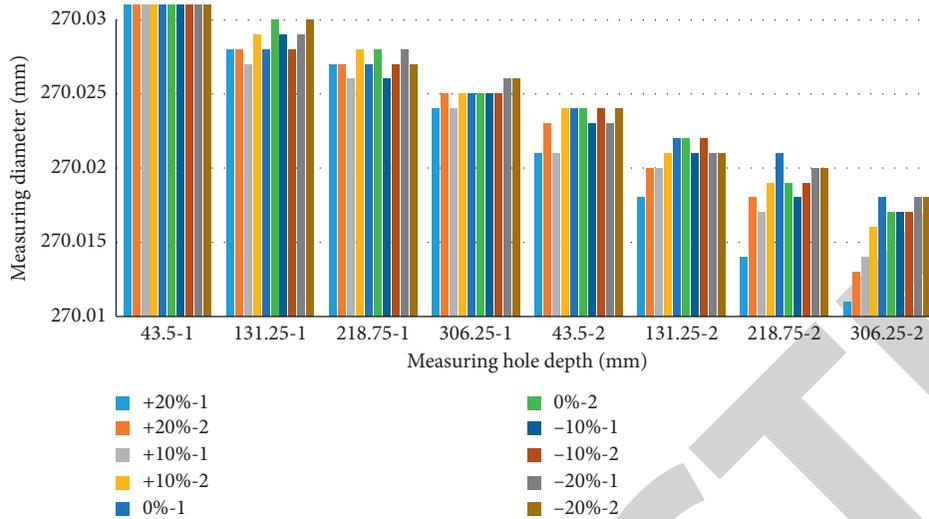


FIGURE 29: Cluster bar graph of measuring result data.

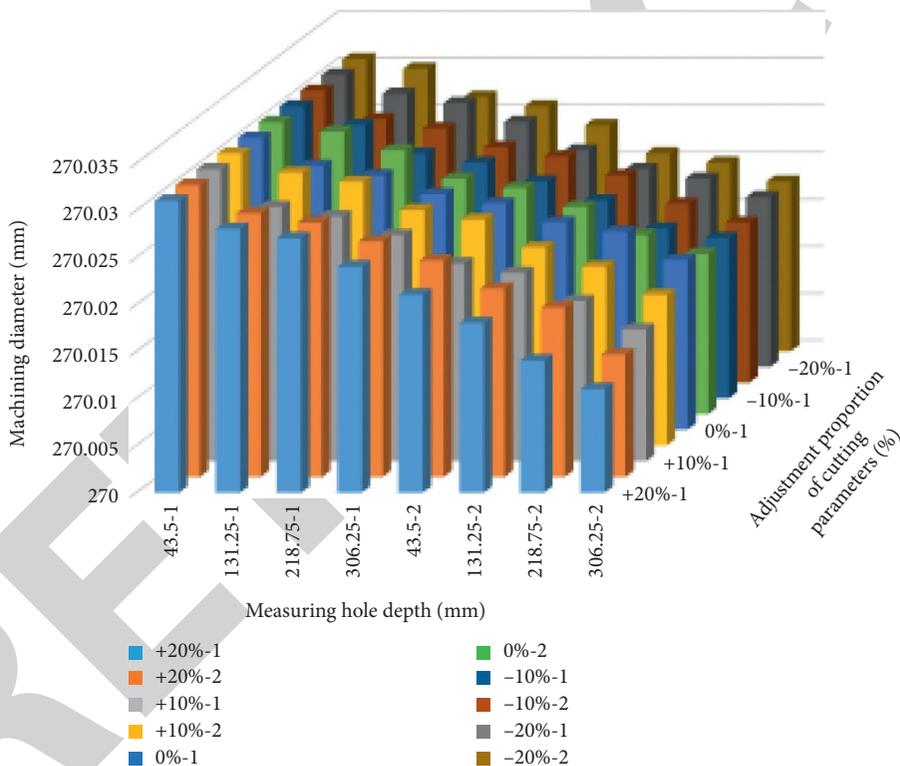


FIGURE 30: Three-dimensional bar graph for measuring result data.

gets worn. The optimum process parameter for fine boring is -10% of the recommended value. In combination with the machining time data in Table 6, it becomes easier to determine the frequency of tool changes.

7. Conclusion

Business managers and technicians, in cooperation with program developers, can achieve precise digital applications by clarifying their digital intentions and establishing rules for data collection and management. Oriented to the actual

needs, integrating information technology and management knowledge to enhance the application technology, such research and development model with cooperation between different application areas is exactly the construction of the information application and service model what we refer to in the implementation guideline of the manufacturing powerhouse [2].

Referring to the requirement of measuring data acquisition from milling a platen for the hydraulic plastic injection machine on a PAMA floor-type CNC milling-boring machine, a simple digital manufacturing information system was built

with logging and process data sharing functions in the Siemens 840D SL CNC controller, combined with common information technologies, to be able to record the measurement data during machining. On this basis, three applications of probe error detection, machine geometry accuracy monitoring, and tool process parameters and life management are realized step by step through the use of big data technology. The new technology achieves its design goals through practical machining process research, tool life management, and verification of the machine maintenance work.

Compared with the existing technology, this solution has the following five advantages: ① based on the common LAN communication, it has no additional electrical equipment and wiring, is low cost, and is easy to implement compared with the typical digital solution; ② NC programming makes the text output less technically challenging, different CNC systems have similar functions, and it is easy to promote a wide range of applications; ③ it can collect unlimited types of data according to the actual needs of their own expansion; ④ based on big data technology, it can be customized according to the needs of the algorithm. The input data are accurate and effective. The calculation results are true, reliable, and strongly referenced; and ⑤ the additional visual communication interface enhanced the readability of the data and the scope of applications.

The automatic measurement data collection and application of touch probes on CNC machine tools is essentially an extension of the digital application of industrial technology, the greatest advantage of which is the ability to save complete process data. Big data technology, however, is a new type of database technology, with powerful data screening, retrieval, and processing performance. Both are fundamental technologies for achieving smart manufacturing. Within the manufacturing industry as a whole, we purchased many smart manufacturing solutions from foreign countries. The localization is not satisfactory due to the large number of related technologies and the different approach of each. In order to develop smart manufacturing technology ourselves, it is inappropriate to place too much emphasis on the entirety system but carving up various fundamental technologies related to it. By objectively analyzing the current situation, segmenting the needs, and completing the technology roadmap, the overall goal is naturally achieved.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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