A MBD Model-driven Automatic Generation Method of On-machine Measuring Program for CNC Machining

Wenhao Zhong¹, Cheng Zhai¹, Yansheng Cao² and Meiqing Wang¹*

¹ School of Mechanical Engineering and Automation Beihang university, Beijing, China
² Intelligent Equipment and Technology Laboratory, Beijing Xinfeng Aerospace Equipment Co. Ltd

*Corresponding author email: wangmq@buaa.edu.cn

Abstract. Aiming at the problem that the programming of on-machine measurement in CNC machining process is heavily dependent on operators and the efficiency is lower, a MBD model-driven automatic generation method of on-machine measuring program is proposed. The characteristics of measuring program is analysed and the relationship between the parameters of measuring cycle and the features of MBD model is built. The approach of PMI (product manufacturing information) data identifying and extracting is presented. The scheme for transforming the PMI data and geometric features to measuring cycle parameters is constructed. In order to make the measuring program adapt to the change of probe position which stored in different tool magazine, the way of collecting the position automatically by OPC DA protocol is provided. On the basis of the proposed methods and approaches, an on-machine measuring program generating software system has been developed. The running result of the system is given, and the feasibility and effectiveness of the method were demonstrated.

Keywords: MBD model; Inspection plan; On-machine measuring program; CNC machining.

1. Introduction

On Machine Inspection (OMI) refers to the automatic inspection of workpieces using of high-precision measuring devices on CNC machine tools, which makes CNC machine tools have the function of part quality inspection. In this kind of inspection, the quality of the workpiece can be checked at any time during the processing of the part, and it is no longer necessary to move the workpiece from the machine tool to the inspection equipment, which greatly affects the processing accuracy and efficiency of the workpiece. In addition, OMI can realize the integration of processing, inspection and error correction. For parts with high precision requirements, pre-inspection before processing can be carried out to control the machining allowance to ensure the dimensional accuracy and reduce the rejection rate. At present, a large number of CNC machine tools have on-machine measurement functions which are generally realized by CNC macro program. As a result of it, higher requirements are put forward for programmers to make programs, which leads to low utilization rate of OMI in the part machining process. Therefore, the realization of the automatic programming of on-machine inspection program has become a focus in the academic and business circles.

Under the guidance of the Made in China 2025 Action Plan, enterprises have carried out the informationization of management and digitalization and intelligentization of manufacturing processes. MBD technology, due to its advanced design-manufacturing-inspection-use integrated characteristic, coupled with the geometric product specifications (GPS), the 3d model definition and analysis technology based on GPS, it provides a technical basis for realizing the automatic transfer and
identification from design stage to the manufacturing and inspection stages [1-2]. However, in the work of quality inspection and management of manufacturing enterprises, the process from the definition of product quality requirements and the proposal of inspection requirements, to the execution of inspection work and the collection of quality data, and to the analysis and prediction of quality data, the information flow and process flow are separated. This discontinuity generally solved by human intelligence at present which is inevitable to result some problems, such as negligence and ambiguity in understanding, delay in implementation, and serious dependence on human experience which makes quality control and management unable to adapt to the diverse needs of enterprises development and change. Therefore, realizing the MBD model-driven automatic generation of on-machine inspection programs has become one of the key issues that need to be resolved to improve inspection efficiency and product quality in the intelligent manufacturing mode. What’s more, the MBD model-driven automatic generation of on-machine measuring program needs to solve two main problems: MBD model-based inspection planning and automatic generation of on-machine measuring program.

In the research of inspection planning based on the MBD model, domestic and foreign scholars mainly focus on the measuring point layout and path optimization of the CMM. Zhang designed and developed a computer-aided inspection planning (CAIP) system with functions including tolerance analysis, measuring point accessibility analysis, measuring point clustering and path planning [3]. Zhao Qianwen et al. developed PMI (Product Manufacturing Information) driven CAIP system [4]. A large number of scholars have conducted a lot of researches on measuring uncertainty evaluation, recognition and extraction of measured feature, and detection path optimization in inspection planning of CMM measurement [5-10] which got a series of achievement.

In terms of on-machine measuring program generation, Liu Libing et al. established a detection path tree model, which realized automatic planning of detection paths and automatic program generation, and applied it in the SSK U6035 machining. However, the method did not involve PMI information [11]. Yu Yanpeng et al. extracted the MBD model information based on the secondary development of UG and formed the inspection task. Then, they transferred inspection tasks to the manufacturing system in workshop using the XML file as a medium. But the problem of it is that measuring program was manually generated by operators [12]. Wang Wenchao et al. realized the contact type based on surface features and the non-contact type based on critical points of detection path planning, but the information of measured feature is manually input, and the integration degree with the MBD model is not high [13]. At present, the mainstream software products on the market that support on-machine inspection planning, such as PowerInspect and PC-DMIS, do not yet support the identification and extraction of PMI in the MBD model. The SIEMENS SINUMERIK series CNC systems provide the guiding function of the on-machine measuring programming, but do not support the analysis of the MBD model [14].

From the perspective of the integration of MBD model design-manufacturing-inspection, this research proposes a MBD model-driven automatic generation method of on-machine measuring program for CNC machining. It includes process model of on-machine measuring planning based on MBD model, automatic extraction of key elements of program and process model of measuring program generation. Finally, the effectiveness of the proposed method is verified through engineering examples.

2. The MBD Model-driven Generation Process Model of On-machine Measuring Program

2.1. Analysis of the Characteristics of On-machine Measuring Program

The on-machine measurement is driven by the measuring program. In order to simplify the measuring operations, mainstream CNC system suppliers such as SIEMENS, FANUC, HEIDENHAIN, etc. all provide on-machine measuring cycles. The operator can complete the programming of the on-machine measurement by inputting and setting relevant parameters. This research takes the measuring cycle CYCLE977 provided by the SIEMENS CNC system as an example, analyses the composition of the on-machine measuring program, and provides guidance for the MBD model-driven program generation method of on-machine measurement.
Table 1. Example of on-machine measuring program using CYCLE977.

| Program block | Explanation of the block | Remarks |
|---------------|--------------------------|---------|
| ;%_N_PLATFORM_MPF | Name of the program block. G17 sets the XOY measurement plane, G90 sets the absolute coordinate programming mode. | Non-essential |
| N10 G90 G17 | | / |
| N20 T="Pro" M06 | T="Pro" gets probe information, “M06” changes tool. | Manually enter |
| N30 G0 X-100.0 Y140.0 | “G0” quickly locates the measurement starting point x-y (-100,140). | Manually enter |
| N40 Z45.0 | “G0” quickly locates the measurement starting point z 45.0. | Manually enter |
| N50 _TUL=0.03 _TLL=0.03 _VMS=0 _NMSP=1 _FA=2 | Define the tolerance value of the measured dimension: _TUL is the upper deviation; _TLL is the lower deviation; _VMS is the measurement speed whose default value is 0; _NMSP is the number of measurements which can be determined according to the measurement needs, _FA is the measurement stroke, the value is 1-10. | Manually enter |
| N60 _MVAR=4 _SETVAL=10.0 _MA=2 ID=-15.0 | _MVAR is the measurement method specified by the system, this example is the rib measurement, _SETVAL is the theoretical value of the dimension, _MA is the measurement direction along the coordinate axis, here is along the Y axis. ID is the depth of detection. | Manually enter |
| N70 CYCLE977 | Call CYCLE977 measurement cycle | / |
| N80 G0 Z75.0 | Move the probe to a safe height determined according to the size of the workpiece. | Manually enter |
| N90 M2 | End of program | / |

**Note:** The parameters related to the automatic compensation are not considered in the example.

It can be seen from table 1 that the on-machine measuring program block can be classified as the following four categories:

**Category 1: Parameters related to the shape, size, tolerance and coordinate system of the measured workpiece.** Among them, G17 is related to the orientation of the geometric feature to which the measured dimension is attached; X-100.0 Y140.0 is related to the geometric size of the measured feature; _SETVAL=10.0 is related to the dimension of the measured geometric feature; _TUL= 0.03 and _TLL=0.03 are both related to the dimension tolerance of the measured feature; _MVAR=4 is related to the contour of the measured geometric feature; _MA=2 is related to the measuring orientation in the coordinate system; ID=-15.0 and Z75.0 are both related to the size and shape of the geometric feature.

**Category 2: Parameters related to the probe.** Among them, T = "Pro" is related to the probe’s position number that "Pro" is the name of the probe installed in the tool magazine. The M06 tool switch command can take the probe out of the tool magazine. In addition, different machine tools may have different probe installation positions and different names.

**Category 3: Parameters related to system settings or fixed values.** These parameters will not change that G90 is absolute programming instruction, M06 is tool switch instruction, G0 is rapid point positioning instruction, M2 is program end instruction and CYCLE977 is measuring cycle instruction.

**Category 4: Parameters related to quality inspection requirements.** _VMS is measurement speed; _NMSP is measurement times; FA is measurement stroke. They are set by the inspection planner.

### 2.2 Generation Strategy of On-machine Measuring Program

As we all know, the MBD model contains information such as geometric dimensions, tolerances, coordinate systems, model composition and geometric features. Therefore, most of the first category of parameters in the measurement program can be obtained through the exploration and analysis of the MBD data. The data access protocols provided by the CNC system, such as Siemens’ OPC DA/UA, FANUC’s FOCAS and HEIDENHAIN’s LSV2, all provide functions to access parameters to the tool management system. For that reason, the second category of parameters in the measuring program related to the probe can be obtained by accessing the CNC system’s tool magazines. Other parameters can be set by inspection planners as required. Based on the above analysis, the generation process of on-machine measuring program is divided into two stages, ① the on-machine measurement planning stage based on the MBD model; ② the customized program generation stage of the measurement for CNC machine tools. The MBD model-driven generation model of on-machine measuring program is shown in figure 1.
The on-machine measurement planning based on MBD model includes two parts: automatic extraction of PMI annotations and analysis of geometric feature, interactive setting of measurement parameters for needs of the inspection tasks. At this stage, the acquisition of related parameters except for probe data and CNC commands in the on-machine measuring program are completed. The customized generation stage of the measuring program for CNC machine tools is as follow: firstly, the probe data is automatically obtained from each tool magazines for workpiece processing; then the planning information and probe data are filled into the program block according to the requirements of program template, and finally the on-machine measuring program is generated. From the above processes, the whole generation process of on-machine measuring program is a completely customized one.

3. On-machine Measurement Planning Based on MBD Model

3.1. Definition of the Relationship between the MBD Inspection Information

The PMI data in the MBD model is associated with geometric features, and the dimensional tolerance and geometric tolerance annotations comply with GPS standard specifications (ISO 1101(E), ISO 5459(E)). The dimensional tolerance information includes dimension type, tolerance zone, relevant requirements and constraints of measured elements and features, etc. this information defines the tolerance requirements of direction and position with regard to a single geometric feature or multiple geometric features after machining. It also establishes the relationship between geometric features and product quality characteristics and requirements. So, the relationship between these information needs to be established by the definition of the data model.

Figure 2 shows the association model between PMI, GPS and geometric features. PMI information includes four parts: tolerance item set, coordinate system and component model datum, associated geometric feature set and other annotation information. Among them, tolerance set include dimensional tolerance and geometric tolerance; dimensional tolerance includes distance, diameter, radius, angle and length. GPS dimensional tolerance, datum and coordinate system are all directly related to geometric features (components and derived features in the measured part). This research mainly discusses the on-machine measurement of dimensional tolerances rather than geometric tolerances.
3.2. The Scheme for Transforming the PMI Data and Geometric Features to Measuring Cycle Parameters

By extracting the PMI annotation data in the MBD model and analysing the geometric features associated with annotation, the scheme for transforming the PMI data and geometric features to measuring cycle parameters can be carried out. This research takes the CYCLE977 measuring cycle provided in the SIEMENS SINUMERIK system as an example to introduce the transforming process based on the MBD model.

The CYCLE977 measuring cycle can realize the measurement of common geometric features such as hole, circular spigot, groove, rib, rectangular spigot and rectangular pocket, and can calculate the size of the workpiece contour [16]. We use plane features as an example to introduce how to automatically anatomy MBD data and obtain parameters such as _SETVAL, _TUL, _TLL, XYZ, _MA and so on which are required by the measuring cycle.

Before introducing the specific planning process, constraints are given out firstly which need to be met for the measuring cycle-oriented inspection planning:

1. The measurement coordinate system should coincide with the machining coordinate system.
2. The measurement direction of features should be consistent with the coordinate axis direction.
3. The measurement plane determines the setting of the processing plane in the measurement. Take the measuring plane with the z-axis upward as an example, the processing plane parameter is set to G17.

**Figure 3.** Process of automatically analysing MBD information to obtain measurement parameters.
As shown in figure 3, the MBD model information is divided into annotation information and geometric feature information through analysis. The methods to obtain each measurement parameters are as follows:

1. **SETVAL**: The nominal value X in the model annotation is SETVAL;
2. **_TUL** and **_TLL**: The theoretical upper deviation +U in the model annotation is _TUL, and the lower deviation -L is _TLL;
3. **_SAFEZ**: It is obtained by analysing geometric feature information. Taking the rib feature as an example, two plane features P1 and P2 are analysed by extracting the features attached to the dimension. Then, the two planes are respectively transformed by UV coordinates, and the eight values of A1, B1, C1, D1, A2, B2, C2, and D2 vertices which are respectively in P1 and P2 plane are calculated. The eight values are transformed to the z-axis coordinate values of the measurement coordinate through the coordinate system transformation. The safety height _SAFEZ must be greater than the maximum value of the z-axis coordinate values of all 8 points;
4. **_ID**: The absolute value of the probe detection depth ID must be greater than the minimum value of the z-axis coordinate values of all 8 points in (3), and less than the maximum value of them;
5. **X, Y**: For the centre point coordinates of ABCD plane (Ux/2, Vx/2), Transforming it through the coordinate system transformation to obtain the values (x, y, z) in the measuring coordinate system. Then, the starting point coordinates values X, Y can be determined by calculating the midpoint coordinates value of the line connecting the two plane centre points;
6. **_MA**: Because CYCEL977 can only measure along the x-axis or y-axis of the measuring coordinate system, it is only necessary to determine whether the measurement direction is x-axis or y-axis. If the difference between the coordinates of the two centre points in the x-axis direction is greater than it in the y-axis direction, the measurement direction _MA is 1, which means measuring along the x-axis. Otherwise, if it is 2, it means measuring along the y-axis;
7. **The plane position relationship**: The feature analysis process obtains the normal vectors n1 and n2 of P1 and P2. The vector m1 is constructed from the centre point of P1 to the midpoint of the two centre points. Setting the angle between the two vectors n1 and m1 as α1, and the angle between the n2 and m2 is α2. If both α1 and α2 are greater than 90°, the two planes are against each other. If one of α1 and α2 is greater than 90° and the other is less than 90°, the two planes are in the same direction, otherwise the two planes face each other.

The analysis processes of geometric features such as groove, rib, rectangular spigot, and rectangular pocket are similar to the above. The measured object of the hole and the circular spigot is cylindrical surface. The anatomy of the cylindrical surface only needs to analyse one plane. In the case of comparing parameter values of two planes, it only refers to the parameters of one plane.

The measurement parameters which are not automatically acquired: _MVAR, _NMSP, _FA, _SAFEZ, _ID, and Z of the measurement starting point are all interactively set by the inspection planner. Among them, _SAFEZ and _ID are restricted by the above allowable range of values, and the measurement method _MVAR is restricted by the following characteristics: groove measurement corresponds to a pair of faced planes; rib measurement corresponds to a pair of against planes; rectangular pocket measurement corresponds to two pairs of faced planes; rectangular spigot measurement corresponds to two pairs of against planes; the hole measurement corresponds to the inner cylindrical surface; the circular spigot measurement corresponds to the outer cylindrical surface.

4. Customized Generation Method of On-machine Measuring Program

After completing the on-machine measurement planning based on the MBD model, it is necessary to obtain the probe data from the specific machine tool, and finally complete the generation of the on-machine measuring program.

4.1. Automatic Extracting of Probe Data

In the on-machine measuring program, it is necessary to use the M6 tool switch command to realize the automatic adjustment of the probe from the tool magazine. The installation position of the probe in each CNC machine is different, also the name, type and size of it are different. Therefore, it is necessary to
make the measuring program adapt to the change of probe position automatically, so as to generate customized measuring programs for different machine tools.

Taking OPC DA data access protocol widely used in Siemens CNC system as an example, this research introduces the method of acquiring probe information. OPC DA server mainly contains three levels of objects: Server, Group and Item. These three levels are from top to bottom. A Server object can contain multiple Group objects, and a Group object can also contain multiple Item objects. OPC DA server is built into Siemens 840D system, and we can just use OPC DA client to access data. The specific probe data collection process is shown in figure 4.

Figure 4. Flowchart of probe data acquisition.

As shown in table 2, the corresponding position of the magazine parameter is given.

Table 2. Parameters of server address for machine tool magazine.

| Setting                                               | Description                                      |
|-------------------------------------------------------|--------------------------------------------------|
| /Tool/Compensation/edgeData[u1,c1,1]                  | The tool type of No.1 tool in No.1 magazine      |
| /Tool/Compensation/edgeData[u1,c2,1]                  | The tool type of No.1 tool in No.2 magazine      |
| ...                                                   | ...                                              |

The value stored under this address is of integer type, in which the value representing the machine tool probe is 710. Traverse all the tools in the tool magazine of the machine tool. The item with the return value of 710 represents the probe of the machine tool. After obtaining the installed position of the probe of the machine tool, the correct on-machine measuring program can be generated for the machine tool.

4.2. Automatic Generation of On-machine Measuring Program

CYCLE977 has 6 kinds of measurement methods: hole measurement, circular spigot measurement, groove measurement, rib measurement, rectangular spigot and rectangular pocket measurement. They respectively correspond to the single digit value 1-6 in the _MVAR parameter. So, we can package the
measuring program corresponding to each method into a program template. After completing the on-machine measurement planning based on the MBD model, the corresponding measurement method of the measured feature and the parameter corresponding to the address of each program block have been completely determined. In addition, the CNC machine IP address, assigned according to the processing task, is filled into to get the name of the probe and the position number in the tool magazine. The above information is filled into the corresponding program template as required to complete the automatic generation of the measuring program. The specific flowchart is shown in figure 5.

5. Verification of the Method

Based on the MBD model-driven automatic generation method of on-machine measuring program, an on-machine measuring program generating software system has been developed. The system is designed and developed using VS2010 and ProToolkit secondary development kit. It realizes the functions of extracting PMI from MBD model, analysing MBD data, on-machine measurement planning for measured features, automatic acquisition of probe information, and automatic generation of on-machine measuring programs on base of template.

The model shown in figure 6 is used to verify the effectiveness of the function. It contains features such as groove, rib, hole, circular spigot, rectangular spigot and rectangular pocket, with dimensions such as distance and diameter respectively marked.

![Figure 6. MBD model (a) and the result of extracting PMI information(b).](image)

Figure 6 shows the on-machine measurement planning interface based on the MBD model and the generated interface of on-machine measuring program.

![Figure 7. The system interface for on-machine measurement planning (a-b) and the result of the generated measuring program (c).](image)

6. Conclusion

The MBD model-driven automatic generation method of on-machine measuring program is of great significance to realize the integration of all-digital designing, manufacturing and inspecting. It can also greatly improve the efficiency of on-machine measuring program generation. Based on the analysis of characteristics of measuring program and the relationship between the parameters of measuring cycle
and the features of MBD model, this research proposes a MBD model-driven automatic generation method of on-machine measuring program, and presents the approach of PMI data identifying and extracting. Also, the research constructed a scheme for transforming the PMI data and geometric features to measuring cycle parameters and a way of collecting the probe position. On the basis of the proposed methods and approaches, an on-machine measuring program generating software system has been developed. Finally, the feasibility of the proposed method and the effectiveness of the software system are verified by a running result of an example.

Acknowledgments
The authors acknowledge the financial support of Open Fund of State Key Laboratory of Intelligent Manufacturing System Technology, Equipment Pre-Research Program of China (No. 41423010301).

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