DEVELOPMENT OF COMPUTER AIDED CALIBRATION MODULE FOR CMMS AND MACHINE TOOLS USING A COMPENSATED STEP GAUGE

HEUIJAE PAHK, JONGHOO KIM
Department of Industrial Engineering, POSTECH, POHANG, KOREA

요 약

이 논문은 스텝게이지와 마이크로 컴퓨터를 이용하여 온라인으로 3차원좌표측정기의 오차를 보정하는 시스템에 관한 것이다. 이때 사용하는 스텝게이지는 미리 교정을 실시하여 그 교정데이타를 컴퓨터상에 저장하고 있다. 측정기의 작업영역안에서 어떠한 방향으로 스텝게이지가 놓여 있어도 초기점을 지정하면 CNC 타입의 코드를 자동으로 생성하여 스텝게이지 측정을 실시하며 그 측정결과는 3차원 좌표측정기의 오차를 보정하는데 사용된다. 결과적으로 경제적이고 실용적인 오차보정 시스템을 구현할 수 있다.

1. Introduction

Error calibration and frequent reverfication of working accuracy of coordinate measuring machines and machine tools are currently acknowledged as essential processes in order to maintain high performance of the equipments and high quality of products. Expensive equipments such as laser interferometers and precision levels were conventionally used for the precise accuracy assessment, and the measurement tasks were very much time consuming and needed trained personnel for the operations.

On the other hand, mechanical artefacts such as step gauges were usually used for quick acceptance tests and error calibration in part, and their geometrical inaccuracy caused some limitations in practical error calibration.

For linear displacement accuracy of CMMs, many national standards such as ANSI/ ASME[2],VDI/VDE[3], BS[1], and manufacturers' association (CMMA) recommend laser interferometers, step gauges or block gauges. Laser interferometers were preferred for complete linear displacement error with high accuracy. However, a technical disadvantage of the laser interferometer is that the laser optics is inserted instead of measuring probe at the probe holder, the result is a bit different from the real measuring accuracy of the whole measuring system, and thus more prone to the practical machine performance. Thus a new measurement system is desirable for rapid,economic error assessment which also can achieve total measuring accuracy.

The development of micro computer and CNC controller technology enables a new error measurement/calibration system using calibrated mechanical artefacts where the data of the geometric inaccuracy(calibration data) are stored. And the measurement paths are generated for the probing of the mechanical artefacts, then error terms are evaluated from the comparison between the stored and measured data. Detail algorithms are implemented for the analysis.

The whole measurement/calibration procedures are computer controlled and driven by the developed user friendly software.

2. Step gauge calibration

Step gauge was partly used for acceptance tests or error calibration of CMMs and machine tools. In the developed system it is fully used in order to assess some geometrical errors and linear displacement accuracy. Prior to being used for the measurement tasks, thus they have been calibrated with respect to more precise equipments in a environment controlled room in cooperation with KRISS(Korea Research Institute Standards and Science) .

The step gauge is usually made of steel, and small blocks are positioned in nominally equal step, 10mm block pitch in common, and both sides of the blocks are machined parallel. The real distance between the reference block and each blocks are of metrological importance, thus a specially designed length calibration system[KRISS] with laser interferometer is used to calibrate the block distances. Both sides of each block is calibrated and they are stored in a data file, Fig.1 shows practical calibration data of 600mm step gauge.

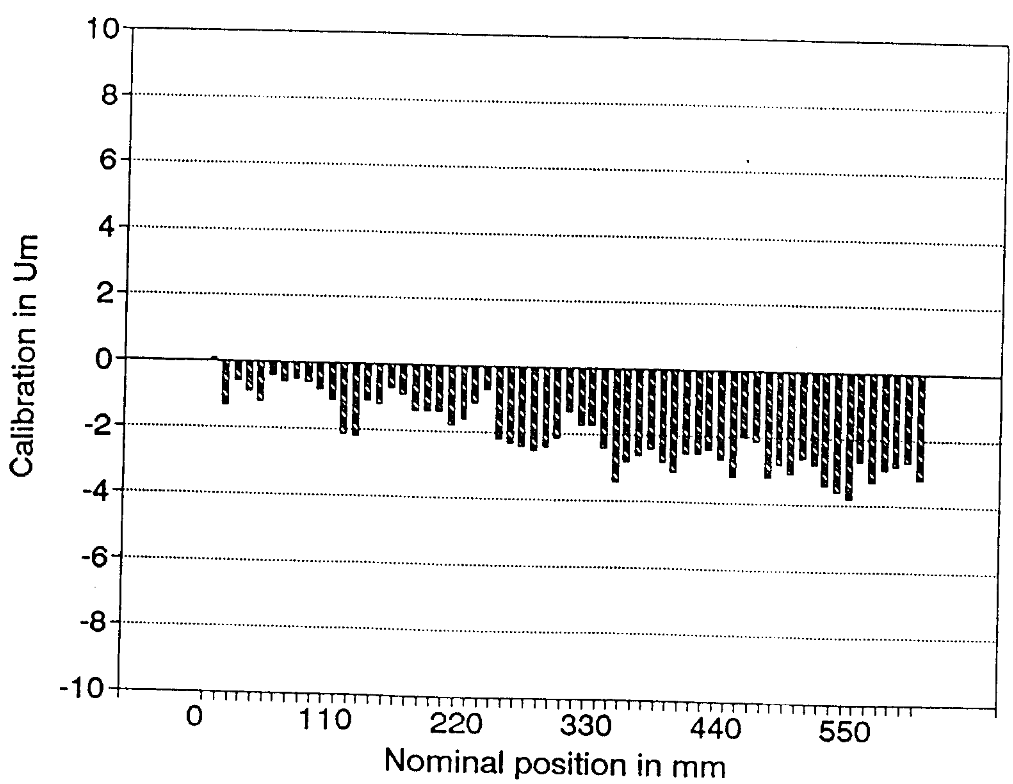

Fig. 1 step gauge calibration

3. Path plan module for gauge measurement

Many modern CMMs of CNC type equip vector driving mechanism, with which target positions can be programmed in proper CNC command then the machine moves to the target points, thus 3 dimensional motion can be planned.

Before planning the path, several intial points are probed in order to inform the CMM of location and position of the step gauge to be probed. As in Fig.2, 16 points are initially probed, 8 points for the beginning block and the other 8 points for the end block. The cross product of vector $\overline{P1P2},\overline{P1P3}$ determimes normal vector N1, and the points P4,P5,P6,P7,P8 determines the width,height,and length of the beginning block. Centre point C1 of the block is obtained through some geometrical calculations with N1,P4,P5,P6,P7, and P8: The same operation is carried on to find the end block's centre point C2. Vector $\overline{C1C2}$ is used instead of N1 or N2 in planning the path to avoid possible misalignment of the normal vector N1 or N2 since they are evaluated from 3 points probing on small area surface of the blocks. The normal vector is to be calculated acurately in that it will be used for error evaluation in later stage.

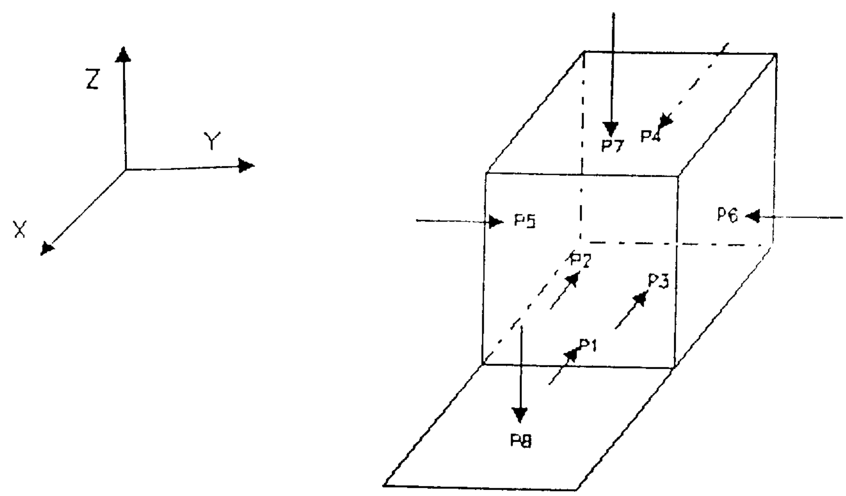

Fig.2 Initial probing for location and position of the step gauge

Implementation of Path plan algorithm

The planned paths are generated in machine code for a specific Jin Young CNC CMM. The idea of implementation of path planning for commercial CMMs are as follows:

Many modern CMMs have teaching mode in which specific measurement operation can be taught by operator, then the CNC system saves the inputted motions. In execution mode the saved informations(actually CNC machine codes for measurement operations) are retrieved and sent to the CNC controller, then executing the measurement operations. These facts show the possibility for intrusion of CNC codes from outside in the teaching mode. That is, if an algorithm can generate proper CNC codes for specific measurement operations. then the generated CNC codes can be passed to the execution mode as if they are from the teaching mode. Thus the path plan algorithm can now be implemented, which inputs initial probing points then outputs corresponding CNC codes. The generated CNC codes are then simulated in the computer graphics which is provided by the CMM manufacturer. In case of step gauge measurement there are two possible ways of path plan, horizontal and vertical path. Fig.3 shows the two paths and operator is supposed to select a proper path in the system.

After simulation on the computer screen, the CNC code is down loaded to the system in the execution mode, then the measurement operations are performed automatically. Fig.4 shows a typical example of the generated CNC codes for step gauge measurement.

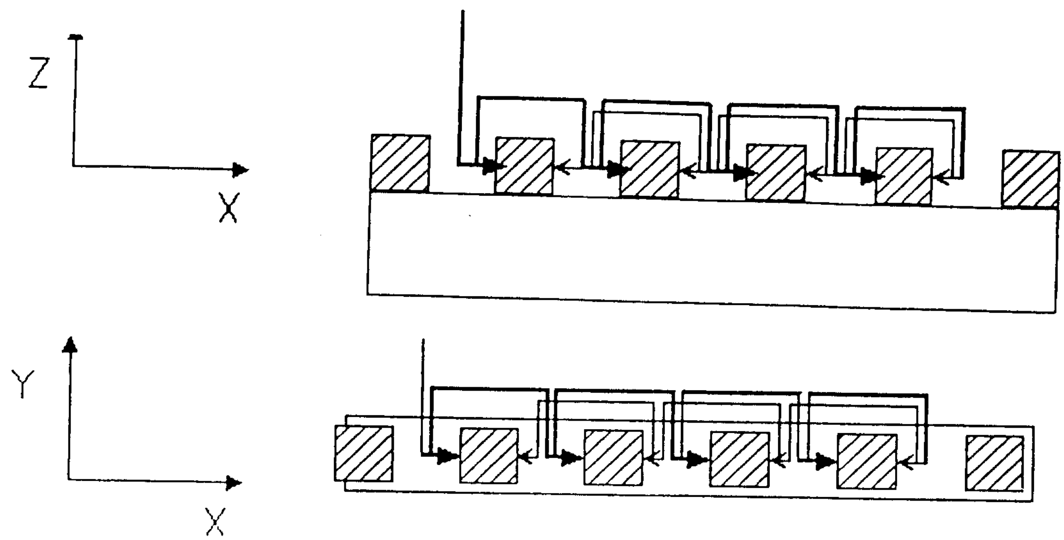

Fig.3 Vertical and horizontal paths for step gauge

```
MV     0.000     0.000    400.000 ;
PO 1 ;
MV   290.877    16.513    201.280 ;
MV   300.877    16.520    201.280 ;
MV   300.865    36.520    201.280 ;
MV   290.865    36.513    201.280 ;
MS   290.862    41.013    201.280 ;
PO 1 ;
MV   290.865    36.513    201.280 ;
MV   300.865    36.520    201.280 ;
MV   300.853    56.519    201.280 ;
MV   290.853    56.513    201.280 ;
MS   290.850    61.013    201.280 ;
              .
              .
              .
END;
```

Fig.4 A typical CNC codes for step gauge measurement

4. Error evaluation module

The gauge probing data are saved into raw data files, and are ready for error evaluation. In this section, an error evaluation module is shown, where influence of machine errors can be calculated from linear diaplacement error from step gauge measurement.

4.1 Linear displacement from step gauge measurement

Similarly, the step gauge measurement results are processed to give linear displacement accuracy or length measurement error.

Calculation of effective radius of probe, R_{eff}

The CMM touch probe mainly consists of three parts: stylus tip, probe stylus, and probe body unit. Measuring force of touch probe, though it is supposed to be within few gram force, can cause elastic deformation of the probe stylus in combination with bending effects and springs of the probe body unit. Thus effective radius of the stylus tip is considered, and it is slightly smaller than the nominal radius of tip. In general, it is recommended that the effective radius, sometimes called pre-travel variation, is to be calculated in the same direction as measurements would take place according to Renishaw manual[5].

The effective radius can be determined from measurement between neighboring blocks whose distance is known, where two close neighboring blocks are desirable in order to avoid possbible introduction of scale errors of the machine. The effective radius is

$$R_{eff} = \frac{\text{(measured block size - actual block size)}}{2} \qquad \text{Eq(1)}$$

where actual block size is the calibrated block size from the calibration data file, and the effective radius calculation is automatically performed during step gauge measurement.

The calculated effctive radius value is saved and then will be used for evaluating linear displacement accuracy from the step gauge measurement.

Evaluation of linear displacement accuracy

The linear displacement accuracy or length measurement error can now be calculated from the measurement data and the calibration data of the step gauge, because there would be no difference unless machine errors exist. As the blocks' sides are accessible from only one direction, say either forward or backward, shown in Fig. 5, error calculation is separately performed for front and back sides of the blocks.

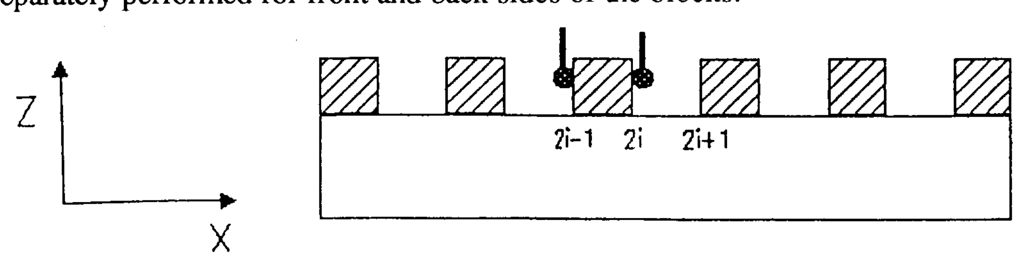

Fig.5 error evaluation for front and back sides in step gauge measurement

As in Fig.5 let $M_{2i-1,j}(X_{2i-1}, Y_{2i-1}, Z_{2i-1})$, $M_{2i,j}(X_{2i}, Y_{2i}, Z_{2i})$ be the jth measurement data at (2i-1)th location and (2i)th sides respectively, and S_{2i-1}, S_{2i} be the actual distance of (2i-

1)th,(2i)th block sides from a reference point, respectively, which can be obtained from the calibration file of the step gauge. Then the errors at (2i-1)th ,(2i)th sides can be evaluated as follows.

Let $XF_{2i-1,j}$,$XB_{2i,j}$ be the jth forward backward measurement error at (2i-1),(2i)th step, respectively.

$$XF_{2i-1,j} = (M_{2i-1,j} - M_{ref}) - (S_{2i-1} - S_{ref}) \quad Eq(2)$$

$$XB_{2i,j} = (M_{2i,j} - M_{ref}) - (S_{2i} - S_{ref}) \quad Eq(3)$$

where M_{ref} is the position of reference point, S_{ref} is actual distance of the reference point from the step gauge origin. It is noted that the measurement data are decomposed into the normal vector $\overline{C1C2}$ direction in order to exclude any mispositional errors of the measuring probe on the block sides.

The forward positional error and two standard deviation can be evaluated from the repetitive forward measurement, and backward positional error and two standard deviation as well.

Thus,forward and backward positional error XF_{2i-1}, $XB_{2i,j}$ and two standard deviation SF_{2i-1}, SB_{2i} are evaluated as follows.

$$XF_{2i-1} = \frac{1}{cycle}\sum_{j=1}^{cycle} XF_{2i-1,j} \quad Eq(4)$$

$$SF_{2i-1} = \sqrt{\left(\frac{1}{(cycle-1)}\sum_{j=1}^{cycle}(XF_{2i-1} - XF_{2i-1,j})^2\right)} \quad Eq(5)$$

$$XB_{2i} = \frac{1}{cycle}\sum_{j=1}^{cycle} XB_{2i,j} \quad Eq(6)$$

$$SB_{2i} = \sqrt{\left(\frac{1}{(cycle-1)}\sum_{j=1}^{cycle}(XB_{2i} - XB_{2i,j})^2\right)} \quad Eq(7)$$

where cycle is the repetitive measurement. In case of step gauge measurement, alternate step is either forward or backward direction, thus the intermediate step can be calculated from interpolation using neighbor blocks' measurement data. Therefore positional errors at intermediate steps can be evaluated, that is,

$$XF_{2i} = \frac{(XF_{2i-1} + XF_{2i+1})}{2} \quad Eq(8)$$

$$XB_{2i-1} = \frac{(XB_{2i-2} + XB_{2i})}{2} \quad Eq(9)$$

and

$$SF_{2i} = \frac{SF_{2i-1} + SF_{2i+1}}{2} \qquad \text{Eq(10)}$$

$$SB_{2i-1} = \frac{SB_{2i-2} + SB_{2i}}{2} \qquad \text{Eq(11)}$$

thus XF_i , XB_i, SF_i, SB_i ,i=1,2,3... are evaluated for at each step blocks of the step gauge. The mean positional error, XM_i can now be calculated as a average of the forward and backward positional error.

$$XM_i = \frac{XF_i + XB_i}{2} \qquad \text{Eq(12)}$$

and the reversal error, XR_i is the difference between the forward and backward measurement errors,

$$XR_i = XB_i - XF_i \qquad \text{Eq(13)}$$

4.2 Error presentation

Computer graphics environments are so fully utilized that the evaluated errors are presented on computer screen, printer or plotter. In case of step gauge measurement, mean positional error,forward and backward positional errors are tabulated with corresponding nominal coordinates of CMM. Also, two standard deviation as well as the reversal error is tabulated at each nominal coordinates, thus complete linear displacement accuracy is performed Practical examples for the step gauge measurement and corresponding error evaluations are shown in section 5.

5. Practical application of the developed system and discussions

Practical measurement procedures for step gauges

A computer controlled commercial CMM of fixed bridge type was chosen for the practical measurement procedures which was installed in metrology lab in POSTECH, and it has to be mentioned that the machine was not in proper calibration state thus bears no relation to the real machine performance.

The gauge measurement system begins with locating the gauges in a working volume of the CMM, as the developed system allows all possible orientation and position for the gauges Once located, the CMM probes the initial points on the gauges ,16 points for step gauge for proper path plan, and the probing data for initial probing are then saved in a temporary file. The developed path plan module is now loaded and inputs the initial probing data, and relevant data such as step size or number of division, then the path plan is performed and the corresponding CNC code is generated for the CMM controller. The CNC code is saved in a data file, and is ready for graphical simulation or execution of the measurement operation. As the CMM performs measurement, the measured data are displayed on the computer screen and saved in a raw datafile. The error evaluation algorithm is now loaded, and the algorithm asks operator to choose two file names :one is the file of gauge calibration and the other is the raw data file of gauge measurement for comparison. In case of step gauge, the position number (or indexing number) of beginning and end blocks of the step gauge has to be inputted in the error evalution stage, as the used section of the step gauge is to be informed for accurate calculation.Then the error evaluation module is loaded, and error calculations are performed as explained in the previous section.

Step gauge measurement

A step gauge is located and measured in a working volume of a CMM. The measurement and analysis procedures are followed as mentioned in the above. As results, the X positional error is shown in Fig.6 giving 8.5 um bandwidth over 230 mm measurement span and 5.0 um repeatibility, which is two standard deviation of 5 repetitive measurements.

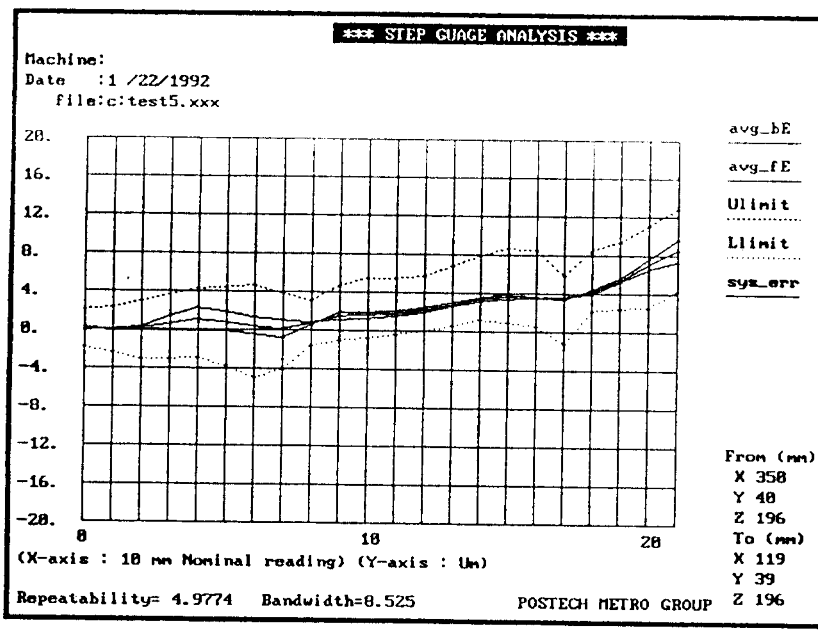

Fig. 6 X axis calibration

As mentioned above, the step gauge measurement can be performed for any orientation in the working volume, thus a diagonal direction is chosen for metrological interest in the working volume. Fig.7 shows the calibration result along the diagonal direction, (364, 297, 195) to (225, 64, 195) mm position in the machine, giving 20.5um bandwidth over 270 mm measurement span.

6. Conclusion and suggestions for further works

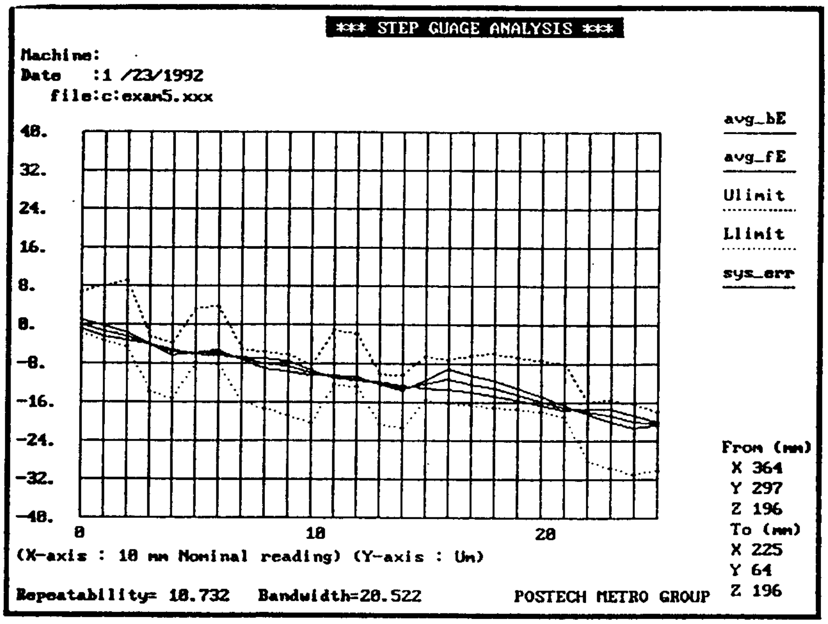

Fig. 7 Diagonal calibration

Conclusion

(1) Computer integrated measurement / error calibration system is developed ,where path planning, measurement operation, error calculation, and geometric error presentation are effciently performed around a commercial CMM and micro computer.

(2) Calibrated mechanical artefacts are found to be useful for assessing machine errors in terms of total measuring accuracy, where their geometric inaccuracies are stored in a form of data file, and are used in error evaluation stage.

(3) For precise error analysis using touch probe, the effective radius evaluation algorithm is implemented, where the effective radius term is calculated automatically in step gauge measurement.

(4) A complete algorithm for linear displacement accuracy (length measurement) of a commercial CMM is implemented with touch probe and calibrated step gauges.

(5) Path plan module for gauge measurement is found to be effcient, where proper paths are planned, simulated, then executed for real measurement operation. Especially, because the path plan module invokes TEACH MODE of a commercial CMM, the developed system can be easily applied to other commercial CMMs.

(6) The developed system is found to be fast and effcient system, thus practical error measurement / calibration are performed in very short time, thus it is applicable to day-to-day calibration or frequent reverification of CMMs.

Suggestions for further research

(1) The path plan module is desirable to generate path plans in universal CNC code such as DMIS, though a specific NC code adapted at the moment.

References

(1)BS 6808:1987 British Standard for Coordinate Measuring Machine, British Standard Institution

(2)ANSI/ASME B89.1.12M-1985, An American National Standard, Methods for Performance Evaluation of Coordinate Measuring Machines, 1985, The American Society of mechanical Engineers.

(3) VDI/VDE 2617

part1 Accuracy of coordinate measuring machines characteristics and their checking generalities,1983

part 2 Measurement task specific measurement uncertainty, 1983

part 3 Components of the measurement deviation of the machine, 1984

(4) Touch Trigger Probe System Users' Guide, Renishaw