NISTIR 4978

A Comparison of National Standards for the Performance Evaluation of Coordinate Measuring Machines in Terms of Length-Based Dimensional Quantities

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November 1992

U.S. DEPARTMENT OF COMMERCE
Barbara Hackman Franklin, Secretary

TECHNOLOGY ADMINISTRATION
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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

This paper compares U.S., German, British and Japanese standards for evaluation of coordinate measuring machines and shows that using a variety of special artifacts the U.S. standard alone specifies separate tests for each of the four modes of length measurements (displacement, position, distance and extension) and that, depending on the number and orientations of faces probed, a bi-directional step gage of the type suggested in the other standards can be used for tests of each of these.

Introduction

A principal means to higher quality in the manufacture of products having dimensioned parts is higher accuracy in both the machines which form the parts and the machines which measure them. The dimensions of parts are of different types, each comprising a different length-based dimensional quantity.

Since modern manufacturing depends on interchangeability of parts traded both domestically and internationally, accuracy in these various types of part dimensions consists not only of conformity of the dimensions to design but conformity of the units of the dimensions to a standard. The international standards of length is the meter, which is defined in terms of the propagation of light in free space. Practical realization of the formal definition is by means of laser interferometry and another length-based dimensional quantity, displacement.

Figure 1 is an engineering drawing representation of an automobile engine which illustrates some of the principal types of geometrical dimensions of discrete parts. These types of geometric features include: A, representing a length or width of the engine block; B, representing the diameter of a cylinder bore; C, representing the distance between the centers (axes) of cylinder holes; D, representing the depth of a blind hole; E, representing the (true) position of a feature relative to the origin of a part coordinate system defined by,

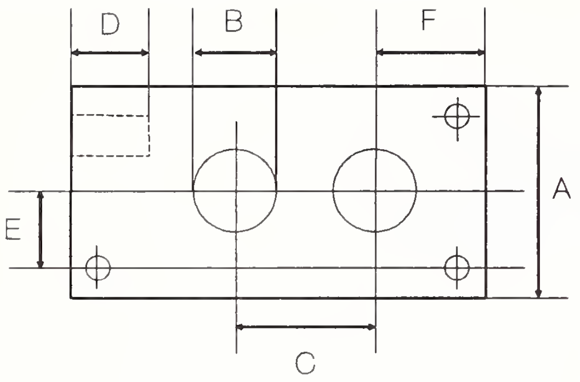

Figure 1 An Engineering Drawing Representation of the Principal Geometrical Dimensions of a Manufactured Discrete Part

for example, reference holes in the oil pan plane; and F, representing the location of the center (axis) of a hole relative to a plane.

Each of the various part features shown in Figure 1 corresponds to a different type length-based measurement quantity: displacement, position, distance, and extension. For example, in this case of the automobile engine, there are extension-type features such as the length of the block and the diameter of cylinders; there are distance-type features such as the spacing of axes of the cylinders; and there are position-type features such as the locations of cylinders relative to reference features such as dowel holes. Features such as the depths of blind bore holes are most akin to a displacement. The significance of this approximate correspondence between types of features and types of length measurements is that in both the manufacture and measurement of dimensioned parts such as these, each of the length-based dimensional quantities involved is susceptible to type-specific errors which propagate and compound in a way which has been described in detail previously [1] and outlined in Appendix A.

For the evaluation of the accuracy of either machine tools or measuring machines, there are two general approaches relative to these part and length measurement types: first, overall evaluation in terms of a machine's ability to produce/measure part dimensions of the extension type; and evaluation of ability to produce/measure the aspects of each of the types — displacement, position, distance, and extension. Representative of the former approach is the German/European VDI/VDE standard for the evaluation of coordinate measuring machines; representative of the latter is the U.S. ANSI B89.1.12.

1. Standard-Based Performance Tests of CMMs

Two industry standards are commonly referenced by U.S. manufacturers of commercial coordinate measuring machines are the U.S. ASME B89.1.12 [2] and German VDI/VDE 2617 [3]. Other major national standards for CMMs are the Japanese JIS B7440 [4] and the British BS 6808 [5].

1.1. The U.S. Standard

American National Standard ASME B89.1.12M-1990 specifies five principal tests for the evaluation of the dimensional measurement capabilities of CMMs. These five performance tests are called: Measuring Repeatability, Linear Displacement Accuracy, Volumetric

Performance, Bi-Directional Length Measurement Capability, and Point-to-Point Probing Performance.

1.1.1 Measuring Repeatability

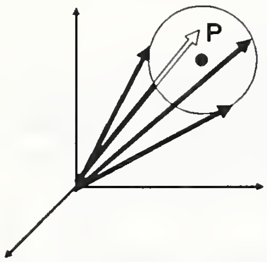

Figure 2 B89.1.12M Performance Test for Measuring Repeatability

The first B89.1.12M machine performance test is measuring repeatability and deals with the capability of the CMM to properly measure position.

In this test a precision reference ball is located at the mid-point of travel of each of the machine's three linear axes. Four widely-spaced non-planar contacts are made with the ball. From this set of four readings are calculated coordinates of the center of the ball. Ten determinations of these center coordinates are so made. The range of the ball center coordinate, that is, the maximum minus the minimum, is determined for each axis.

The measuring repeatability is, then, this spread in the calculated locations of the center of the ball for the ten repeats. Thus this "measuring repeatability" performance test gives an estimate, on a per axis basis, of the variability in measurement of position at a single location:

$$\Delta P_x = | P_{xmax} - P_{xmin} | . \qquad (1)$$

1.1.2. Linear Displacement Accuracy

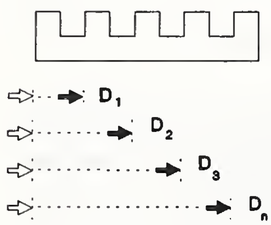

Figure 3 B89.1.12M Performance Test for Displacement Accuracy

The second B89.1.12M machine performance test, linear displacement accuracy, deals in the word's of the standard with the conformance of the machine's scales to the international standard of length.

In this test, either a step gage or a laser interferometer may be used. For each axis, the step gage or laser interferometer is oriented along a line parallel to that axis through the center of the work zone. Measurements are made for at least ten equal intervals, which are specified to be greater than 25 mm and less than one-tenth the axis length. The accuracy for a given step is the difference between the step gage calibration or laser reading and the mean corrected machine reading. The linear displacement accuracy is then the sum of the magnitudes of the maximum positive and maximum negative errors.

Thus this "linear displacement accuracy" performance test gives an estimate of the maximum error in the ability to measure from any location to any other location in the full travel and in the measurement of displacement-type features (see Appendix A):

$$\Delta D = | \Delta D_{max+} | + | \Delta D_{max-} | . \qquad (2)$$

1.1.3. Volumetric Performance

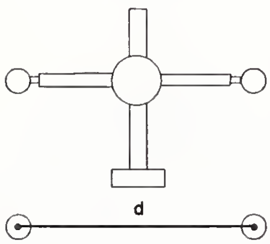

Figure 4 B89.1.12M Performance Test for Volumetric Performance

The third B89.1.12M test, volumetric performance, deals with the ability of the machine to properly measure relative distance (indirectly intercomparing the length scales on the various machine axes and testing for imperfections of machine geometry).

In this test, a fixed-value, uncalibrated ball bar with a length 100 mm shorter than the machine axis is used. At least four points are probed on each ball to locate its center and the distance between the center of the two balls is calculated. For CMMs with nearly cubic workzones, the process is repeated at each of twenty orientations of the ball bar located at edges, face diagonals and body diagonals of the cube. The "tolerance" on volumetric performance" is the absolute value of the range of observed values for the twenty orientations.

Thus this "volumetric performance" test gives an estimate of the maximum distance error anywhere within the arbitrary-metric space of the machine:

$$\Delta d = | d_{max} - d_{min} | . \qquad (3)$$

1.1.4. Bi-Directional Length Measurement Capability

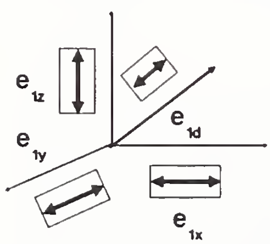

Figure 5 B89.1.12M Performance Test for Bi-Directional Length Accuracy

The fourth B89.1.12M machine performance test, bi-directional length measurement capability, deals with the ability of the machine to properly measure extension in rectilinear modes.

In this test, a single gage block of calibrated length of the order of 25 mm is located where parts are typically measured within the workzone. The length of the gage block is measured at each of four orientations of the block, three parallel to the axes of the machine and one parallel to an off-axis diagonal. The tolerance on bi-directional length measurement capability is the maximum deviation of the observed values from the known value of the length of the gage block.

This "bi-directional length measurement capability" performance test thus gives an estimate of the maximum error in such a measurement of extension of rectilinear-type objects:

$$\Delta e_x = | e_{obs} - e_{true} |_{max} . \qquad (4)$$

1.1.5. Point-to-Point Probing Performance

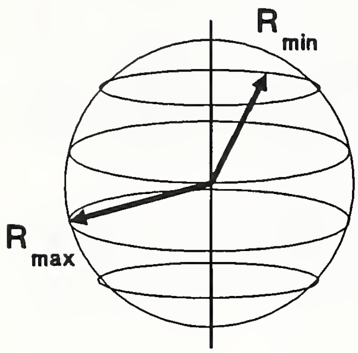

Figure 6 B89.1.12M Performance Test for Point-to-Point Probing

The fifth B89.1.12M machine performance test, point-to-point probing performance, length measurement capability, deals with the ability of the machine to properly measure locations in radial directions. According to the standard, the test is devised to establish the magnitude of errors contributed by probing sequences for probes used in the point-to-point mode.

In this test, a roundness-calibrated precision reference ball is located within the workzone. The ball is probed at each of forty-nine points, twelve equally spaced on each of four circles of specified elevations plus one at the upper pole. From the set of forty-nine points, a sphere center is calculated and a radius determined for each measurement point.

The point-to-point performance is the maximum radius minus the minimum radius. This is functionally equivalent to the range of deviations of the forty-nine radii from the actual, but unknown, radius. Thus this "point-to-point probing" performance test gives an estimate of the maximum error in a measurement of the radial extension of an object in any orientation:

$$\Delta e_R = | e_{Rmax} - e_{Rmin} | . \qquad (5)$$

2. Relation of B89.1.12M Performance Tests to Dimensions of Parts Measured

Each of the five B89.1.12M performance tests just described assesses the ability of a coordinate measuring machine to accurately perform one of the four fundamental types of dimensional measurements, displacement, position, distance and extension, three of which correspond to dimensions of physical objects, such as the features of an automobile engine block shown schematically here.

· The "measuring repeatability" performance test assesses the ability of the CMM to repeatably measure position of features such as that of a cylinder hole relative to the part coordinate system of the block (shown here as a corner and in practice defined by features such as dowel holes and pan-plate surfaces).

· The "volumetric performance" test assesses the ability of the CMM to uniformly measure relative distance such as that between the centers of successive cylinder holes independent of their orientation.

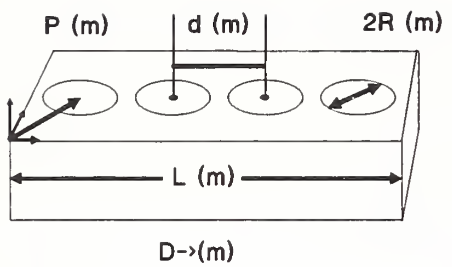

Figure 7 Features of an Automobile Engine Block By Dimensional Type

· The "bi-directional length measurement accuracy" performance test assesses the ability of the CMM to accurately measure extension of features such as the length of the block.

· The "point-to-point probing" performance test assesses the ability of the CMM to accurately measure radial extension type features such as the internal diameter of cylinder holes, the external diameter of the mating pistons, as well as the locations of planes to centers (such as feature F in Figure 1).

· Finally, the "linear displacement accuracy" performance test assesses the ability of the CMM to accurately measure displacement itself, relative to the international standard of length, as well as displacement-, position-, distance-, and extension-type features on objects.

3. Intercomparison of Standards for CMM Performance Testing

The principal standards dealing with performance evaluation of coordinate measuring machines are those of Germany (VDI/VDE 2617), Britain (BS 6808), and Japan (JIS B7440) as well as that of the U.S. (ASME B89.1.12) just discussed. Table 1 summarizes the test artifacts each of these standards specifies and the measurement quantity to which each artifact-based test corresponds.

[1] This is the "rectilinear" type of extension where L(left) and R(right) simply denote any pair of opposite-facing plane parallel boundaries.

[2] This is the "radial" type of extension where L(left) and C(center) simply denote any location on the surface of a sphere relative to the center.

For assessment of what it terms "length measuring uncertainty", the German VDI/VDE 2617 standard allows a step gauge or gauge blocks used in either one of two modes: either bi-directional (here called the high-option, corresponding to what is here called an extension-type mode); or uni-directional (here called the low-option, corresponding to what is here called a displacement-type mode).

For assessment of what it terms "length measurement uncertainty", the British BS 6808 standard allows either a step gage or gauge blocks required to be used in a bi-directional (extension-type) mode; the standard explicitly forbids use of the uni-directional (displacement) mode for assessing length measurement uncertainty.

Table 1 Comparison of the Principal Standards for CMM Performance Evaluation in Terms of the Artifacts They Specify and the Type of Length Measurement to Which Each Artifact-Based Test Corresponds

Artifact Specified	*Length Mode*	*VDI/VDE 2617*	*BS 6808*	*JIS B7440*	*ASME B89.1.12*
Step Gage Gage Block	Extension [1] (L-to-R)	High Option	Required	Required	Required
Step Gage Gage Block	Displacement (L-to-L)	Low Option	Forbidden	Required	Option 2
Ball Bar	Distance (C-to-C)	...	...	,,,	Required
Laser Interferometer	Displacement (L-to-L)	Reqd for Axes > 1m	...	...	Option 1
Reference Ball	Position (C-to-O)	Required	...	...	Required
Reference Ball	Extension [2] (L-to-C)	Required	...	...	Required

For assessment of what it terms "length measuring accuracy", the Japanese JIS B7440 standard allows either a step gauge or gauge blocks required to be used in a bi-directional (extension) mode. In addition, for assessment of "linear displacement accuracy", the Japanese standard allows either a step gage or "block gauges" used in a uni-directional (displacement) mode.

For assessment of what it terms "bi-directional length measurement accuracy", the American ASME B89.1.12(1990) standard requires a gauge block used in a bi-directional (extension) mode. In addition, the American standard specifies a number of other tests. For assessment of "linear displacement accuracy", the American standard allows use of either a laser interferometer (a displacement-measuring device) or a step gauge used in a uni-directional (displacement) mode. For assessment of "volumetric performance", this standard suggests use of a ball bar, a device which provides a fixed but uncalibrated distance. For assessment of "position repeatability", it requires use of an uncalibrated precision reference ball, which provides for a well-defined location (i.e. position). And, finally, for assessment of "point-to-point probing", it requires use of a roundness-calibrated precision reference ball (which allows a measure of non- or omni-directional extension). In general, the test of CMM performance required by the majority of these standards deals with the evaluation of the capability to measure extension; only the U.S. standard specifies tests for all four unit-of-length-based quantities.

As indicated by the table, while described by slightly different nomenclature (the British standard calling it "length measurement uncertainty", the Japanese "length measuring accuracy", and the American "bi-directional length measuring accuracy"), three of these four national standards specify either a step gauge, gauge blocks or end standards used in a bi-directional mode for measurement of the extension.

The German standard does not require, but allows as an option, bi-directional measurements, for assessing "length measuring capability". Since that standard defines "length" as only "the distance between parallel planes", independent of whether they are the same- or opposite-facing, bi-directional (extension) and uni-directional (displacement) measurements are each allowed.

In addition to tests of extension-measurement capabilities, the Japanese, U.S. and German have functional equivalents of the U.S.'s separate "linear displacement accuracy" test, the U.S. standard explicitly allowing the optional use for the test of either laser interferometer systems or artifacts such as step gauges used in a uni-directional mode.

Only the U.S. standard specifies separate tests related to each of the unit-of-length-based measurement quantities which a CMM has the capability to measure, including distance and position as well as extension and displacement. For assessment of what it calls "volumetric performance", the U.S. standard requires use of gage blocks or a ball bar, a device which provides a fixed but uncalibrated distance. For assessment of "position repeatability", it requires use of a precision reference ball, which provides for a well-defined location relative to an origin or reference datum (i.e. position). And, finally, for assessment of "point-to-point probing", it requires use of a precision reference ball, which — while its radius is not calibrated — allows one to set an upper limit on omni-directional or radial extension errors, in contrast to the bi-directional or longitudinal extension described above.

As shown in Appendix B, however, the bi-directional step gage referred to in other national standards can be used for measurements in each of the four length modes. In either case, however, that of application of the U.S. standard with its variety of reference artifacts (end standards, ball bars and precision reference spheres) or use of a bi-directional step gage as outlined in Appendix B, one may begin to separate sources of error by type as a basis for remedial efforts or improved machine-system design.

Conclusion

With modern computer-controlled coordinate measuring machines and the parts they inspect being widely traded internationally, evaluation of the performance of CMMs has become an important matter for their producers and users. As a result, standards bodies in four major industrial nations — the U.S., Japan, Germany and Great Britain — have independently developed documentary standards for the evaluation of the performance of CMMs.

This paper intercompares the tests prescribed by each of these standards in terms of a previously reported taxonomy of length-based measurements which: 1) makes distinctions among extension, distance, position and displacement types of length measurement; and 2) shows that these types are ordered such that — in CMM measurements — errors propagate from the simplest type, displacement, through position and distance, to the most complex type, extension, which is the type most often thought of as "length".

The principal result of this intercomparison is to show that while the principal measure of accuracy in CMMs is a test of ability to measure an extension type of feature (with three of the standards requiring such a bi-directional test and the fourth allowing a uni-directional displacement-type test as an acceptable alternative), only the U.S. standard requiring tests for each of the four length-measurement types. In doing so, it has in common with the other standards the most important measure of CMM accuracy while also providing a more comprehensive and unambiguous basis for a separation-of-variables analysis of overall system performance.

Appendix A. Relations of Errors Specific to Types of Length Measurements

This appendix outlines briefly how each of the various types of length-based dimensional quantities is susceptible to type-specific errors which, in certain cases, propagate and compound in succession as described in detail in Ref 1. The example here is that of a coordinate measuring machine equipped with laser interferometers as scales and a touch-fire probe used to measure an extension-type feature such as the length of a block.

The first and most basic measurement this CMM must be able to make is that of displacement, where the machine accurately measures the change in location of its own moving element relative to its internal scale, in this case, a laser interferometer system. The errors in this measurement are shown formally as:

$$\Delta D = \Delta D\ (\delta D, \delta\lambda), \tag{A1}$$

which says that the total error in the displacement measurement ΔD is a function of $\delta\lambda$, the error in the vacuum wavelength of the laser, plus δD, errors specific to the displacement measurement, such as improper dead-path compensation and variations in the index of refraction along the path of the moving mirror.

The second basic measurement this CMM must be able to make is that of position, where the machine accurately measures the location of a feature, that is the center of that feature, relative to an origin, that is, a reference datum, fixed relative to the frame of the machine. The errors in this measurement are shown formally as:

$$\Delta P = \Delta P\ (\delta P, \Delta D), \tag{A2}$$

which says that the total error in the position measurement ΔP is a function of ΔD, the total error in displacement measurement, plus δP, errors specific to the position measurement, such as Abbe error due to carriage tilt and non-directional variation in probing.

The third basic measurement this CMM must be able to make is that of distance, where the machine accurately measures the separation of the centers of two features on an object, whether artifact standard or manufactured part. The errors in this measurement are shown formally as:

$$\Delta d = \Delta d\ (\delta d, \Delta P), \qquad \text{(A3)}$$

which says that the total error in the distance measurement Δd is a function of ΔP, the total error in position measurements, plus δd, errors specific to the distance measurement, such as the cosine error of misalignment between the axis of the measuring machine and that of the object.

Finally, the fourth and last basic measurement this CMM must be able to make is that of extension, where the machine accurately measures the separation of two opposite-facing boundaries of a feature, such as that of the end faces of a block. The errors in this measurement are shown formally as:

$$\Delta e = \Delta e\ (\delta d, \Delta e), \qquad \text{(A4)}$$

which says that the total error in the extension measurement Δe is a function of Δd, the total error in distance measurement, plus δe, which are errors specific to the extension measurement, such those due to improper compensation for the finite extent of the probe.

Appendix B. Use of a Step Gauge in Four Measurement-Quantity Modes

This Appendix shows how, depending on the number and relative orientations of the boundaries of features involved: 1) which the four pure types of length-based measurements various features of step gages most closely correspond; and 2) how a bi-directional step gauge may be used to perform performance tests corresponding to these types.

First, a feature of the gage which has as its boundaries, for example, the left face of the first step (1L) and the left face of another step (e.g. 4L) corresponds to the blind-hole D in Figure 1 and is here called a displacement-type feature. This use of the term displacement is in the same sense that the US B89 standard uses measurement of such features to assess what it calls "linear displacement accuracy", with a unidirectional approach to feature boundaries. (It should be noted, however, that measurements of displacement-type features can be susceptible to errors associated with those of position per se, such as errors due to Abbe offset combined with stage pitch).

Second, a feature of the gage which has as its boundaries, for example, the left face of the first step when that face is treated as a reference datum or origin of coordinates (1L) to the center of another step (½[4R+4L]) is here called a radial-extension type feature. This feature corresponds to determination of the separation of a boundary from a center (and vice versa), and corresponds to feature F in Figure 1. Errors associated with measurement of such features are evaluated by means of the B89 "point-to-point" performance test.

Third, a feature of the gage which has as its boundaries the center of the first step ([½[1L + 1R]) and the center of another step (e.g. ½[4L+4R]) is a what is here called a distance-type of feature, since it involves the separation of the centers of two features. This corresponds to feature C in Figure 1. Note, however, that when one of the features is formally designated an origin of part coordinates, the location of the second center relative to the first is then a position-type feature.

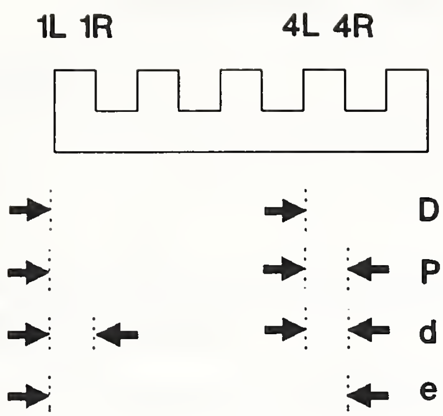

Figure A1 Use of Step Gage in Displacement, Position, Distance, and Extension Modes of Length Measurement

Finally, a feature which has as its boundaries a face of one step (1L) and an opposite face on another step (e.g. 4R), corresponding to feature A in Figure 1, is an extension-type feature.

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NIST-114A (REV. 3-89)	U.S. DEPARTMENT OF COMMERCE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY	1. PUBLICATION OR REPORT NUMBER NISTIR 4978
	BIBLIOGRAPHIC DATA SHEET	2. PERFORMING ORGANIZATION REPORT NUMBER
		3. PUBLICATION DATE NOVEMBER 1992

4. TITLE AND SUBTITLE

A Comparison of National Standards for the Performance Evaluation of Coordinate Measuring Machines in Terms of Length-Based Dimensional Quantities

5. AUTHOR(S)

Dr. Dennis A. Swyt

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

10. SUPPLEMENTARY NOTES

☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

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12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

ASME B89.1.12; calibration artifacts; coordinate measuring machines; JIS B7440, B56808; national standards; VDI/VDE 2617

13. AVAILABILITY

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- [X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES

14

15. PRICE

A02

ELECTRONIC FORM