

REPORT

CMM VERIFICATION AND GRADING

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September 1997

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ABSTRACT

National Physical Laboratory and industrial collaborators have recently completed a project concerned with research and dissemination on co-ordinate measuring machine (CMM) verification, grading and technology transfer. The overall aim of the work was to provide guidelines, codes of practice and procedures for the effective and reliable use of CMMs. The production of these guidelines, codes of practice and procedures was based on the use of mathematical models of measurement, where appropriate, and on a wide range of actual and simulated measurements obtained by NPL and industry. Account was taken of work undertaken at other laboratories, particularly within Europe and the USA, and the work by relevant ISO Committees and Working Groups.

This document provides a summary of the results of this work and covers procedures for verifying large volume CMMs according to ISO 10360-2, interim checking procedures, operating conditions and sample handling and the virtual CMM. Further technical documentation is indicated in bibliography sections. This work was supported by the National Measurement System Policy Unit of the Department of Trade and Industry, UK.

NPL Report CLM 1

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ISSN 1369-6777

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Approved on behalf of the Managing Director, NPL
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1 PROCEDURES FOR IMPLEMENTING ISO 10360-2 ON LARGE VOLUME CMMS

1.1 INTRODUCTION

Large CMMs with (some of their) axes several metres long are used by industry to measure the shape of a diverse range of *large* manufactured parts, including:

- Aircraft components, such as wing sections, fuselage parts, helicopter blades and the principal components of landing gear.
- Car bodies, parts of buses and coaches.
- Large turbine rotors used for power generation.

In view of the dimensions of such systems they are more prone than the medium-sized CMMs to the influence of the lack of rigidity of the foundations on which the CMM is mounted and to the component parts themselves. However, some such CMMs are quite versatile, having more than one measuring head and sophisticated probe systems which can be used to probe internal surfaces and small features, and some are capable of providing the accuracies demanded by the aerospace and automotive industries.

Just as for medium-sized CMMs, industry requires reliable coordinate measurement of parts such as the above, and it is equally necessary that a large CMM has its performance as stated by the manufacturer appropriately verified. The standard specification ISO 10360-2 for verifying the performance of CMMs relies on the use of length standards for this purpose. It is a simple test which in principle applies to CMMs of any physical size. In Clause 4.2.2.2 of ISO 10360-2 it is recommended that the longest length of a material standard is at least 67% of the longest space diagonal of the CMM. In practice, therefore, it is relatively easy using length bars to verify the performance of a CMM whose principal dimensions are 1 metre or less. Guidelines already exist (BS 6808 Part 3) to help the user to undertake such performance verifications. However, verification of the performance of CMMs, the principal dimension of which significantly exceed 1 m, require special attention since large mechanical reference artefacts with the necessary dimensional stability are not easily mounted in a sufficient number of positions and orientations as demanded by ISO 10360-2.

ISO 10360-2 permits large CMMs to be verified using "staged" measurements of a length standard: the standard, of say 1 m in length, is moved along a specific measuring line, overlapping its successive positions in such a way as to cover the required physical length. Staging is formally defined in BS 6808: Part 1, Clause 402 as the moving of a gauge from a first position to a second position such that a series of measurements started in the first position may be continued in the second position with the results related to the first.

Implementation of ISO 10360-2 on large CMMs is nevertheless laborious, time consuming and insufficiently accurate (because of its susceptibility to error propagation) when used with well-established standards such as length bars and step gauges.

Alternative approaches to verifying large CMMs, involving laser interferometry, have also previously been attempted, but only in *ad hoc* ways; these too have not provided a general solution. It was clear, therefore, that further practical work needed to be carried out before a procedure could be written to implement ISO 10360-2 on large CMMs.

One objective of the work was to consider the use of *mechanical reference artefacts* for the performance verification of CMMs, specifically in respect of

- The design and construction of large artefacts having the property that they are capable of being calibrated on CMMs of normal size.
- The development of a method for calibrating the large artefacts on normal-size CMMs.
- A proposed extension of ISO 10360-2 to permit the performance of large CMMs to be verified using the artefact.

A second objective was to assess the extent to which *laser-interferometer displacement transducers* can be used to assess the length-measuring performance of large CMMs.

1.2 THE DEVELOPMENT OF PRACTICAL MEASUREMENT PROCEDURES - VIA MECHANICAL REFERENCE ARTEFACTS

The aim of this activity was to develop practical and cost-effective procedures for using mechanical reference artefacts for the performance verification of large CMMs. The work carried out consisted of three subtasks:

- Development of a methodology and prototype software for the accurate calibration of large artefacts by compact CMMs.
- Design and construction of a large reference artefact suitable for the verification of large CMMs according to ISO 10360-2 procedures.
- Verification of large CMMs using the calibrated large reference artefact and methodologies and software.

In addition, a further activity involving the comparison of artefact and laser interferometer-based techniques, is described later.

1.2.1 *Development of a methodology and software for the accurate calibration of large artefacts by compact CMMs*

A situation that arises in the calibration of large or complex artefacts is that not all of the relevant surfaces of the artefact can be probed without moving the artefact. The problem of relating measurements taken in different artefact positions can be solved by attaching spheres rigidly to the artefact, either directly or through jigs, and determining the positions of (subsets of) the sphere centres for each position of the artefact. The position of three (non-collinear) points are necessary and sufficient to determine a frame of reference. Thus, if the artefact is moved from position to position but the positions of three or more points that move rigidly with the artefact are tracked, it is possible to relate the different positions of the artefact to a common frame of reference. (There is no requirement that the same three spheres are measured in all frames of reference.) The measurements of the artefact's surfaces taken in the different positions to one frame of reference can then be transformed back into one frame of reference, thereby creating a self-consistent set of data points.

A comprehensive mathematical model of repositioning experiments and corresponding software – *position-calibration software* – has been developed to perform an analysis of repositioning data. In addition the software calculates a range of statistics associated with estimates of the transformation parameters and related quantities. This software is completely flexible with respect to number of spheres, number of positions and measurement strategy. The software also provides initial estimates of all the parameters and in addition performs validation checks on the data.

A series of experiments on plain setting rings (ring gauges) and step gauges were performed to demonstrate that repositioning methods can provide accurate calibration information. The aim of the step gauge experiment was to use repositioning to calibrate an artefact larger than the working volume of a CMM and compare the results with independent calibration information. The artefact chosen was a 1 m Check Master step gauge manufactured by Mitutoyu Mfg. Co. Ltd., Japan, that had been recently calibrated at NPL. The experiments were carried out on NPL's Zeiss UPMC 550 CMM. This CMM has a longest axis of 550 mm so the experiment involved measuring an artefact nearly double the longest axis of the CMM. The step gauge was mounted on a steel frame to which were attached ten Zirconia spheres of diameter 20 mm and sphericity 1 micrometre. The step gauge was measured in four positions, corresponding to the initial position and then three translations approximately in line with the axis of the step gauge. The complete experiment was repeated with the artefact and its mounting rotated through approximately 180°.

The results of the experiments undertaken confirmed the feasibility of repositioning methods for calibrating large artefacts by compact CMMs. Taking an overview of the step gauge experiment, the CMM used has a length measuring capability of $\pm (1.3 + L/400)$. The steps measured were up to 900 mm apart so that a benchmark accuracy for the repositioning method was ± 3.5 micrometres. The actual results agreed with the reference results to ± 2.0 micrometres or better, well within the target. All discrepancies could be accounted for by

CMM error, without repositioning and the agreement of the mathematical model with the measurement data to the order of 0.6 micrometres was extremely encouraging. Further application of the position calibration software has been in the calibration of a large reference artefact designed and constructed by NPL and collaborators.

During the development of the methodologies and software and the execution of the various experiments, a number of general points emerged and should be taken into account when designing calibration strategies using repositioning:

Probing of the reference spheres. The spheres used in the experiments described above had a sphericity of 1 micrometre. As the target accuracies for the calibration of the artefacts were of the order of a few micrometres, it is clear that the spheres themselves could give rise to some significant measurement error. In order to achieve high accuracy calibrations, it is recommended that 20 or more points are measured on each sphere (suitably distributed) or that spheres with higher sphericity are used in order to define more accurately the sphere centres.

Position of the reference spheres. Measurement strategies which exploit symmetry in the positions of the require much less programming of the CMM in order to gather the measurements.

Mounting the reference spheres directly on the artefact. Many artefacts have tapped holes or could be designed to have tapped holes. For such artefacts, reference spheres on stalks with standardised threads at one end can be mounted easily on to the artefact. This is the preferred choice as it ensures that the reference spheres and artefact can be treated as a rigid body.

Use of jigs. If jigs are to be employed, there are advantages in using standard jigs for classes of similar artefacts:

- The sphere positions can be calibrated before the artefact is mounted and this additional calibration information incorporated into the data analysis. (The position calibration software allows for this.)
- CMM control software for probing the spheres can be more readily reused.

There are also disadvantages in the use of jigs:

- Jigs can restrict access to the artefact.
- Care has to be taken to ensure that any artefact mounted does not suffer any additional stress by being overly constrained. To minimise difficulties with this, it is recommended that the artefact and jig should be made of materials with similar thermal expansion properties.

Sequentially identifiable measurement strategies. Measurement strategies are termed *identifiable* if initial estimates of transformation parameters linking the frames of reference can be determined automatically from the sphere measurements. An example of an identifiable strategy is one with the property that from one frame of reference to the next at least three spheres are measured in both frames of reference (there is no requirement that the same three spheres are measured in all frames of reference). The advantage of such strategies is that it is much easier to detect exactly when any change in the relative positions of the spheres takes place.

1.2.2 *Design and construction of a large reference artefact*

A length artefact, or more strictly a *length-artefact system*, for verifying the performance of large CMMs has been designed and is currently under construction. The design meets the requirements to be:

- Structurally stable
- Light and rigid
- Easily supported and positioned
- Portable
- Modular design
- Readily assembled and disassembled
- Variable size (up to 5 m in length)
- Straightforward construction
- Readily reproducible
- Capable of traceable calibration.

The system consists of four 1 m and two 0.5 m tubular sections with end flanges, all made of carbon fibre; see Figure 1. By locking the sections together semi-kinematically, artefacts can be formed having a range of discrete lengths from 1 m to 5 m in steps of 0.5 m. The manner of locking ensures that the geometry of the combined sections is highly repeatable. Ceramic spheres are mounted on measuring stations on each section. They are used as references in repositioning measurements to calibrate the artefact and then to carry calibration information (such as distances between sphere centres or sphere centre coordinates in a specified frame of reference).

The design is versatile in that by using an additional cubical mount to which the sections can be attached, L-, T-, V- and X-shaped two- and three-dimensional artefacts can be assembled; see Figure 2.

Experiments and finite element analysis on the rigidity of the carbon-fibre composite tubes have been performed so that any bending corrections can be applied during calibration and use of the artefact in CMM verification. Therefore, it was not necessary to introduce the additional complication of an integral system such as one based on laser-interferometer

displacement, for monitoring the distortion of the artefact under load. If required, any bending can be cancelled out using a reversal measurement strategy.

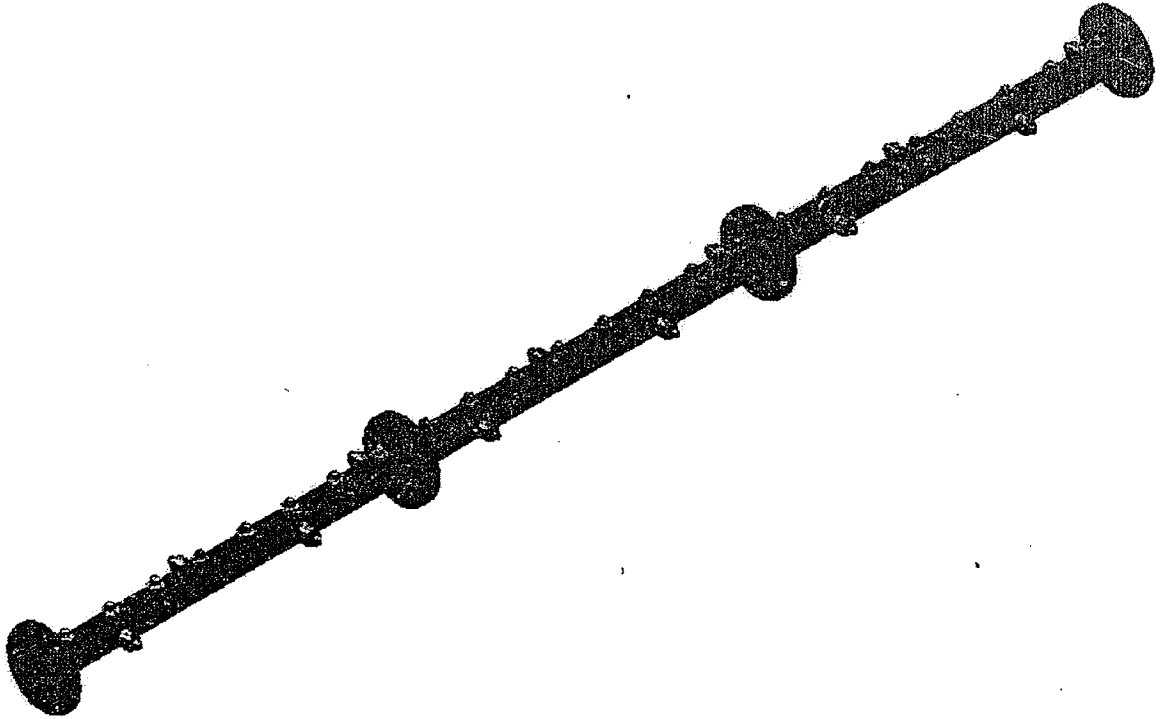


Figure 1. Three 1 m modules of the large reference artefacts assembled in line.

The artefact is supported when used for CMM performance verification by a substructure carried on a central, light, stable pillar. The pillar can be bolted to the CMM table or weighed down using sand bags, for example. The substructure is also made from a carbon-fibre tube, which additionally serves as a container for transporting the artefact. A further support at one end provides extra stability for safety. The design is capable of orientating the artefact in all positions required for performance verification to ISO 10360-2.

1.2.3 *Verification of large CMMs using the calibrated large reference artefact and methodologies and software*

A reliable method of calibrating the artefact using repositioning methods has been developed. First, each module is individually measured by probing all its spheres, using staged measurements if necessary, and recording the measurements obtained. Then, pairs of sections are locked together. Each coupling region is then measured in turn by positioning the composite artefact in a way that provides probe access to all spheres in the coupling region, and again recording the measurements. The position-calibration software can then determine the transformation parameters that relate the various frames of reference and at the same time calculate the calibration information in terms of the positions of the spheres in a fixed frame of reference (and hence *all* inter-sphere distances). Estimates of the standard uncertainties of

these distances are also calculated. Procedures for the calibration and use of the artefact in an ISO 10360-type CMM verification have been drafted and will be released once the artefact has been commissioned.

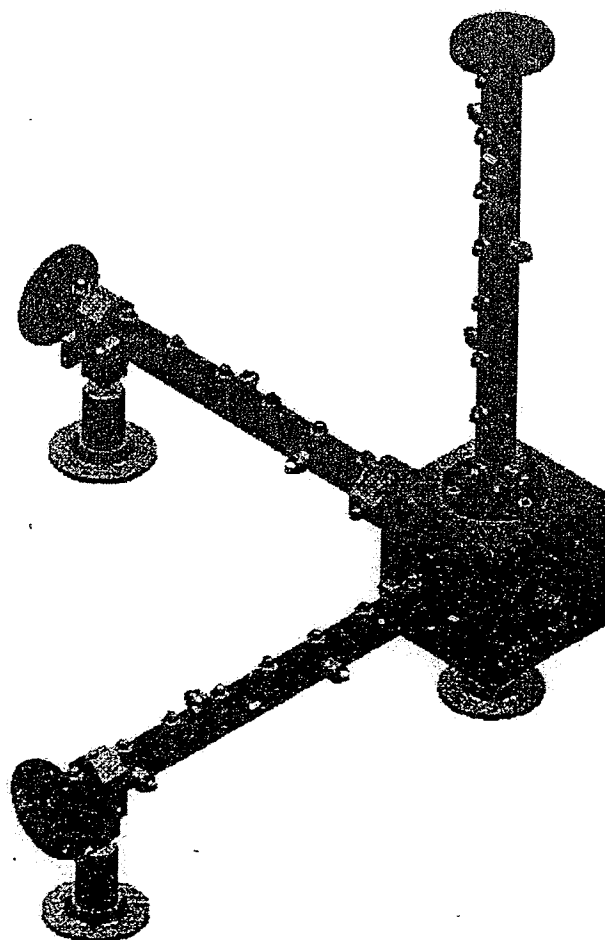


Figure 2. Three modules of the large reference artefact attached to the titanium cube to give a three dimensional artefact.

It should be noted that the strict application of ISO 10360-2 involves the use of bi-directional length measurements between opposing plane faces. For the use of the composite artefact the measurements involve probing (some of) the main spheres on the artefact, from which lengths are calculated. Although probing errors would often be significant relative to the geometrical errors of a standard-sized CMM, the reverse can be expected to be true for a large CMM, and thus the probing of spheres rather than that of opposing faces is not seen as a main source of uncertainty. The intention is to work with the appropriate ISO Committee (ISO/TC 213/WG 10, Dimensional and Geometrical Coordinate Measurement) to develop a new version of ISO 10360-2 which applies to large CMMs and is based on probing reference spheres on a large artefact.

The use of the artefact in a more comprehensive check of CMM behaviour has also been investigated.

The reference artefact not only holds 1-dimensional calibration information in terms of *distances* between spheres but also 3-dimensional calibration in terms of the relative *positions* of the spheres. Thus, the artefact can be regarded as a 1-dimensional ball "plate" or *ball gauge*. Numerical simulations carried out (see Part 2) show that such ball gauges can be used to determine accurate estimates of CMM parametric errors if an appropriate measurement strategy is used.

Although the artefact has been designed to address the problem of verifying large CMMs, the design can be scaled down and applied to the verification/checking of standard sized CMMs. In fact the 0.5 m and 1.0 m modules could prove to be important artefacts in this regard. Compared to step gauges, for example, they are:

- easier to manufacture: most components items are available off the shelf,

- lighter,
- as stable,
- simpler to probe in that there is no need to maintain an accurate measuring line.

In addition, they hold 3-dimensional calibration information. Furthermore, self-calibration techniques developed at NPL eliminate the need for their accurate calibration over an above the requirement to set a single scale. This can be done most easily in conjunction with a gauge block, but other approaches are possible.

1.3 DEVELOPING PRACTICAL MEASUREMENT PROCEDURES VIA LASER-INTERFEROMETER TRANSDUCER METHODS

This activity investigated the use of laser-interferometer displacement transducer method for assessing the length-measurement performance of large CMMs. The work involved three sub-tasks:

- The development of a test bench to evaluate the static and dynamical performance of a interferometer system.
- Analysis of results and the correlation of environmental effects with displacement measurements.
- The comparison of artefact and laser-based methods in large CMM verification.

The work in these subtasks is now summarised.

1.3.1 *The development of a test bench to evaluate the static and dynamical performance of a interferometer system*

A five metre Invar bar was set up in a normal "office" environment close to a number of large casement windows. An interferometer block of a laser interferometer displacement transducer was fixed to one end of the bar and a retroreflector to the other end. In this way, it was possible to monitor the apparent length of the bar under various environmental conditions. The effect of physically shielding the air path in the interferometer loop by a simple arrangement of cardboard tubes was also investigated.

A series of dynamic tests were carried out by measuring a cylindrical five meter Invar bar mounted on the NPL fifty meter tape bench facility. The bar was supported a three points using precision vee blocks and placed between the rails of the tape bench. A moveable carriage with a spring steel cantilever holding a steel shoe with a vee slot milled into it to locate with the fixed ball at either end of the bar was manufactured. This carriage travelled on the rails of the tape bench and held the cube corner/retro-reflector of the laser interferometer displacement transducer.

1.3.2 *Analysis of results and the correlation of environmental effects with displacement measurements*

The results of these experiments show that laser interferometer displacement transducers are only suitable for the characterisation of CMMs in good environments. Shielding the air around the measurement path can have some benefit but can introduce operational difficulties. The main problem with a laser displacement transducer in a poor environment is not so much moving air but the changes in temperature the moving air generally brings with it.

1.3.3 *Comparison of artefact- and laser-interferometer-based techniques*

The main findings of the comparison of the use of mechanical reference artefact and laser-interferometer measurement techniques for CMM performance verification are summarised below. The comparison is on the basis of

- cost,
- environmental influences,
- speed of measurement, and
- interpretation of results.

Cost. Although the initial cost of a laser-interferometer system is high, firms and organisations involved with accurate dimensional measurement often possess laser interferometers. Alternatively, laser interferometers can be hired from specialist firms at a moderate cost. Commercial mechanical artefacts are reasonably expensive, for example, a 2 m long step gauge with all its mounting accessories is likely to cost in the region of £10,000, and calibration costs could add another £1,500 to this price. However, it is possible that, like laser interferometers, such artefacts could be hired.

Environmental influences. The most serious environmental influence is that of temperature. The laser interferometer is prone to the disturbing effects of temperature gradients in the air in the vicinity of the CMM, but the effects of *uniform* variation from 20 °C are small. For a mechanical reference artefact made from conventional materials the influence of temperature on the calibrated length is significant. Compensation for this influence can be made, given the thermal expansion coefficient of the material from which the artefact is predominantly constructed. It is to be noted that, since the expansivity of reference artefacts is not always known as accurately as required in practice, the user is advised to contact the artefact manufacturer for definitive information. Temperature is less of an effect for the types of composite materials considered in the design of the large reference artefact.

The influence of vibration can disturb the laser beam when used over large distances, but is likely to be a secondary problem for conventional medium-sized and small CMMs. In the worse cases it is possible that the beam is deflected completely from the retroreflecting device, thus interrupting the beam. Additionally, poor mounting of a large mechanical

reference artefact can cause false triggering of the CMMs probe when mechanical vibration is present.

General contamination can have a small influence on the refractive index of the air in the measurement path of an interferometer. It is likely that a larger effect results from the presence of dirt or other physical contamination on the reference surfaces of an artefact.

Speed of measurement. In deciding which of the two methods will be quicker, it is necessary to consider the *overall* time that it takes the CMM user to perform all the processes associated with the measurements. In the case of the laser interferometer:

- An adjustable retroreflector needs to be fitted to the probe system of the CMM and the laser interferometer has to be mounted at various positions on the table of the CMM with a means of directing the beam of the interferometer in the direction of the retroreflector.
- The next steps are to program the CMM to move from one end to the other of the test line specified by the CMM operator, to observe the CMM physically making this move, and to ensure that the laser beam remains on the retroreflector the whole time. This ought to be no problem for modern CMMs with vector drives applied to the CMM axes, but may be a more demanding problem from CMMs without such drives.
- Special consideration needs to be given to the collection of data. For example it is most likely that spatial co-ordinate data will have to be collected when the CMM has stopped moving. The reason for this is that significant errors can occur due to differences at the precise moment measurements are taken by the laser interferometer and the corresponding moment that the co-ordinate data is collected by the CMM itself.
- The final steps are to make the test measurements, collect and process the data and compare the CMM values with the values obtained with the laser interferometer.

In the case of the mechanical artefact, the main considerations are as follows:

- Suitable mounting systems must be available for the artefact.
- The CMM has to be programmed to measure the co-ordinates of the reference (calibrated) features on the artefact, with several supplementary probings normally being required for alignment purposes.
- The reference points should be measured in a quasi-static condition using the CMM's probe in the same way as it would be in practice.
- The test measurements have to be collected, processed and the results compared with the calibration information associated with the artefact.

Interpretation of the measurement results. The measurements of spatial co-ordinates, and hence lengths, obtained from the two verification methods are undoubtedly different. When using the laser interferometer the measurements may be taken dynamically, without the CMM stopping, or quasi-statically, with the CMM pausing briefly (perhaps a second or so) between significant axial movements, or statically, with the CMM pausing for a significant period (perhaps many seconds) between axial movements. In the case of the mechanical reference artefact the CMM generally will be in the vicinity of a relatively small feature in order to contact the reference surface at least once and several times in the case of spherical targets.

When measurements are taken using the laser interferometer method, the CMM's probe is not used to touch a surface and therefore any software compensation applied as a consequence of the probe touching a surface is not in general invoked. Indeed, the CMM user should establish from the supplier precisely what is being recorded by the CMM's measurement system when taking measurements in a way that is not normally employed. It is also important to determine whether the CMM's software routines correct for geometrical errors. In the case of measuring mechanical artefacts, the CMM performs in a similar way to that when measuring conventional components, and hence the problems associated with the laser-interferometer approach should not occur.

Recommendations. In general, a combination of both the laser interferometer and the mechanical reference artefact methods is likely to provide the most realistic picture of the performance of large and large-to-medium size CMMs sited in a good thermal environment.

In the case of CMMs sited in a poor thermal environment the conventional mechanical reference artefact may be better, and artefacts designed to reduce the influences of thermal effects should be better still.

For medium and small CMMs, where the influence of either software applied to compensate for geometrical errors, or the probe errors (particularly when probing effects are likely to be significant), the mechanical reference artefact will provide the most reliable information. Nevertheless, the laser interferometer may provide a fast method of checking whether the CMM's geometrical parameters have changed significantly.

Both methods should be seriously considered for CMM performance verification. However, in most cases, and especially when formal traceability of the complete CMM measurement system is required, the mechanical artefact may have an advantage. In the USA more emphasis is given to the role of the laser interferometer to provide traceability to the metre (*via* the ANSI/ASME standard for CMMs). However, great care is required to ensure that the CMM user fully understands which corrections are being applied by the CMM's software.

1.4 SUMMARY

The following summarises the main conclusions and recommendations that arose from the execution of these activities.

- 1 A methodology for the calibration of large and/or complex artefacts using repositioning methods has been established.
- 2 A comprehensive software package – position-calibration software – has been developed to analyse data gathered in repositioning experiments.
- 3 A new type of reference artefact suitable for the verification of large CMMs according to the principles of ISO 10360-2 has been designed and should be commissioned by Autumn 1997.
- 4 A calibration procedure has been developed for the reference artefact based on repositioning methods.
- 5 A procedure for its use in CMM verification has been drafted and will be released when the artefact is commissioned.
- 6 The use of laser-based techniques for large CMM verification have been investigated.
- 7 Both artefact- and laser- based methods are of value in large CMM verification.

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2 GUIDELINES AND PROCEDURES FOR INTERIM CHECKING BY THE USER

2.1 INTRODUCTION

In the vast majority of cases, a CMM will undergo a comprehensive and thorough calibration procedure before delivery to the customer. This procedure will seldom, if ever, be repeated. When a CMM is delivered an acceptance test, normally in accordance with BS 6808 or ISO 10360-2, is performed by the manufacturer to demonstrate to the user that certain aspects of the CMM's performance are within specification according to a nationally or internationally recognised specification standard. These specification standards include clauses which require other tests to be performed at regular intervals to ensure that the CMM continues to conform to the specifications. These tests are of two types:

- periodic reverification, and
- interim checking.

Periodic reverification essentially involves repeating the acceptance test at yearly intervals. The advantage of performing this test is that drift in CMM performance from the initial acceptance testing can be identified, albeit up to a year afterwards. The disadvantage is that the measurement activity involves the measurement of special artefacts and is generally quite unlike the majority of routine measurements made with a CMM.

Interim checking is carried out between formal periodic reverifications. The purpose of the checks is to provide the user with confidence in the measurements made by the CMM. The complexity of such an interim check will vary greatly between users. In some cases very detailed checking of the CMM will be required, verging on a complete *recalibration* of a

CMM, in its fullest sense. In other cases, a very selective test will be required.

There are a number of different levels of checking depending on the degree of confidence with which the CMM needs to be characterised.

- Class 1.* Verification of all degrees of freedom of the CMM accounting for any temperature variations;
- Class 2.* Verification of the entire working volume of the CMM using a standard artefact such as a ball- or hole-plate (a two-dimensional plate with regularly spaced features, usually holes or spheres;
- Class 3.* Verification of the space envelope of interest using a master artefact representing the workpiece features measured in the user's usual application;
- Class 4.* Verification of just the working volume of interest using standard artefacts, for example, length bars.

The type and availability of specialised dimensional metrology equipment and the data-analysis software required to perform Class 1 checks have been published in the literature. The method provides a comprehensive assessment of the errors of a CMM at the expense of the sheer complexity of the different experimental set-ups required to undertake the work. Because of their comprehensiveness, Class 1 checks are very valuable. Although, in principle, accredited laboratories could offer a calibration service for Class 1 checks, the service would necessitate the use of specialised calibration equipment such as ultra-high accuracy differential levels, precise straight-edges and various laser interferometer equipment. However, the CMM manufacturers are in a far better position to offer such services because they will have tailored the calibration equipment to meet the particular needs of their own CMMs. For this reason, this work presented here has not considered the provision of a methodology for Class 1 checks.

Class 2 checks provide a method by which a CMM can be checked using calibrated artefacts. Compared to a Class 1 check, the measurements are quick to perform and the results so obtained take account of the geometrical errors of the CMM. Class 2 checks are valuable because they provide models of the geometrical imperfections (parametric errors) of a CMM and thus the basis for many subsequent computations, including the provision of activity-specific uncertainties associated with a wide range of measurement activities. Ball-plates and hole-plates can be used for this purpose and are applicable to a wide range of CMMs. The proper application of Class 2 techniques depends critically on the use of appropriately designed measurement strategies and the availability of reliable software to determine estimates of the CMM parametric errors.

Class 3 methods are important because they can represent an accurate match with the type of measurement required by the user. Therefore, these methods represent a very reliable

activity-related calibration technique, which additionally can usually be performed rapidly. If the calibration information associated with the artefacts has been determined in a traceable manner, the Class three method can also confer traceability to the associated CMM measurements. However, each check provides information relevant only to associated measurement task and a large number of master artefacts would be required to cover the whole range of components required by certain CMM users.

Class 4 methods are usually regarded as performance-verification methods. As performed in current practice, they are rather restrictive in the conclusions that can be drawn from a CMM assessment, because only the CMM's ability to measure length is tested. However, the advantages of the technique are that it uses artefacts in common use in industry and are capable of being calibrated using methods traceable to standards for length. Class 4 checks can be carried out by several UKAS-accredited laboratories, for example in the verification of a CMM in accordance with the requirements of ISO 10360-2.

2.2 PROCEDURES FOR THE CLASS 2 TECHNIQUE

The aim of this activity was to develop procedures for Class 2 checking, i.e., for verifying the entire working volume of the CMM using a standard artefact such as a ball- or hole-plate. The work consisted of three main subactivities:

- Development of comprehensive mathematical models for the parametric errors associated with common CMM architectures
- Design of optimal measurement strategies for Class 2 checking
- Development of software for Class 2 checking CMMs from the measurement of standard artefacts.

The work on each of these activities is now summarised.

2.2.1 *Comprehensive mathematical models for the parametric errors associated with common CMM architectures*

The parametric errors of a CMM can be described by a *parametric error model*. Such a model, once established for a particular CMM, describes the *geometrical imperfections* of the CMM, and can be used therefore to estimate the actual geometrical behaviour of the machine. Specifically, knowing the scale readings (the x -, y - and z -values) provided by the CMM for any measurement point in the working volume, the model estimates the corrections that need to be made to these values in order to yield error-free measurements. The corrections can be used to provide measurement data of greater accuracy or to estimate uncertainties associated with the measurements.

The main features of the modelling are:

- The three CMM scale readings specify uniquely the position of the probe head, both in terms of position and orientation. Thus, the actual behaviour of the CMM can be described as a function of these scale readings.
- The scale readings x are an idealised representation of the CMM position so that the actual position x^* of the probe head can be modelled as $x^* = x + e$ where e is an error correction term that varies with position. In general, e has a positional component and a rotational component which takes into account the probe stylus offset.

Two types of model of CMM behaviour were considered: *kinematic* and *empirical*. The kinematic model is based on a superposition of the behaviour of the three axes of the CMM, each described as a function of the corresponding scale reading. For motion along the x -axis, the behaviour of the probe housing of the CMM is described by six functions of x , three giving the position of a fixed point on the probe housing and three specifying the rotation angles that describe the roll, pitch and yaw along the x -axis. The y - and z - axes are treated similarly and thus the model is represented in terms of eighteen functions, each of a single variable (x , y or z).

The way the 18 functions combine is determined by the CMM architecture: moving bridge, fixed bridge, moving column, fixed column. Additionally, there may be three *orthogonality*, or out-of-squareness, errors. Hence, there can be a total of 21 errors. Each of these error functions is termed a *parameter* (hence *parametric* error model) and is typically modelled by a simple *empirical (mathematical) function* (such as a low-degree polynomial or a spline with a small number of specified knots) containing an appropriate number of coefficients.

The empirical parametric error models developed in the project represent a new comprehensive class of parametric error models which include the kinematic models as a special case. They make no assumption about the CMM architecture and are capable of describing the repeatable motion of a rigid body in three dimensions that depends on three length transducer (scale) readings. The empirical models are defined by six functions, three determining the position of the probe housing and three determining the orientation with each function depending on all three scale readings. These six functions can be represented as a sum of tensor products, where each product term is a polynomial or spline basis function. These parametric error models have been analysed in terms of

- numerical stability: what information is required to specify all the parametric errors linearisations
- relationships between empirical and kinematic models
- constraints required to eliminate degrees of freedom (often a cause of confusion)

2.2.2 Optimal measurement strategies for Class 2 checking

For the Class 2 checking of a CMM, a standard artefact, such as a ball plate, is placed in a number of positions within the working volume of the CMM and the scale readings corresponding to measurements using various probes of the balls on the plate are recorded. The fact that the ball plate is a rigid body and the calibration information associated with the artefact can be used to estimate the CMM parametric errors. The aim of this activity was to derive a method of obtaining *unbiased* estimates of the parametric errors and use this method in numerical simulations to determine measurement strategies which produce *accurate* (statistically *efficient*) estimates. Factors which will effect the accuracy of these estimates include:

- the parametric error model
- the repeatability of the machine error
- the design of the ball plate
- the positioning of the ball plate
- the probing strategy
- the type of calibration information associated with the ball plate
- the accuracy of the calibration information
- the method of data analysis

The accuracy of the estimates can be gauged by the standard uncertainties of the

- sphere centre coordinates in a fixed frame of reference
- transformation parameters
- parametric error parameters
- error function evaluated at specified points within the working volume of the CMM

These quantities are absolute measures of accuracy and do not take into account correlation between the fitted parameters nor reflect that what is usually of interest is the change in relative error within the working volume. For this reason we also examine the standard uncertainties of the distances between pairs of

- sphere centres
- points within the working volume

These latter two quantities are independent of the choice of the frame of reference and can more easily be compared with the CMM accuracy.

The key stages in the approach adopted were:

- the development of a comprehensive model of a Class 2 experiment which took proper account of the CMM parametric errors, the positions of the sphere on the ball plate, the transformations linking the frame of reference of the ball plate from one measurement

position to another and the CMM random measurement error,

- the development of solution algorithms to provide unbiased estimates of solution parameters along with their standard uncertainties.

From these, it was possible to build a comprehensive numerical simulation tool that could be used to give reliable estimates of the solution parameters and associated uncertainties for any given ball plate experiment.

During the project new measurement strategies were developed which allow for the simultaneous calibration of the ball plate and the estimation of the CMM errors, independently of the model of CMM parametric error. Such strategies generally involve at least one rotation and translation of the plate. An extensive set of numerical simulations were performed to analyse the effect of the various factors on the estimates and their uncertainties. The experiments showed that there are overwhelming advantages in adopting the self-calibration strategies. For such a strategy, correlation between the sphere centre positions, the transformation parameters and the error parameters are greatly reduced leading to a more accurate determination of the parametric error function values, the object of primary interest. The need to perform potentially expensive calibrations of the plate is also largely eliminated; all that is required is additional calibration information to fix the global scale.

A Class 2 checking experiment should also contain *model-validation*, i.e., confirmation that the measured data is sufficiently representative of machine behaviour and that the model is able to explain this behaviour adequately. There are straightforward methods for performing this validation.

2.2.3 *Software for Class 2 checking of CMMs from the measurement of standard artefacts*

Based on the mathematical model of a class 2 experiment, a reference implementation of algorithms to determine parametric error from measured data and the calibration information has been developed:

- The software addresses the true computational aim, no simplifying assumptions or linearisations are made.
- The software produces efficient estimates of the solution parameters for the mathematical model described above. The incorporation of weights in the model allows for a large range of models of CMM error to be covered.
- The functionality of the software covers an almost limitless range of class 2 experiments. In particular, it can cater for any model of CMM behaviour (through the use of fixed interfaces), any ball plate geometry, and any measurement strategy.

- The software implements stable numerical procedures. In particular orthogonal factorisation methods are used throughout.
- The software implements algorithms with proven convergence characteristics.
- The implementation has been thoroughly tested. In particular, all derivative calculations have been tested against finite-difference calculations and solution estimates have been validated using linear search methods.

Moreover, the software also includes extensive data generation modules.

2.3 PROCEDURES FOR THE CLASS 3 TECHNIQUE

Class 3 checking traditionally involves the use of calibrated master artefacts such as step gauges, ring gauges, ball gauges and spheres to assess directly the ability of a CMM to measure an artefact of that type. The substitution or comparator principle forms the basis for this approach. Three main activities are now considered:

- Use of the substitution principle to measure a Class 3 artefact
- Use of Class 3 artefacts to determine the systematic error behaviour of a CMM
- Determination of the systematic error behaviour of a CMM by the fusing of Class 3 and Class 2 measurements

The work on each of these activities is now summarised.

2.3.1 *The use of the substitution principle to measure a Class 3 artefact*

By choosing a master artefact that has comparable properties to that of a production workpiece feature, information on how well that feature can be measured by the CMM can be deduced. For instance, measurements of a ring gauge can be used to deduce the uncertainties of measurement of sections of a cylinder in corresponding positions in the working volume of the CMM. This approach is essentially that of the *comparator* or *substitution* method.

The use of this approach is an important Class 3 procedure. Work on this approach was carried out by NPL in committee as part of international standardisation activities (Part 5). The current status of this work is an advanced draft of an ISO standard on the use of the substitution method for making traceable measurements with CMMs. The substitution method takes measurements both of a calibrated master artefact and the feature of concern.

The main steps in the method for the measurement are as follows:

- Prepare a suitable measurement strategy for the feature
- Position the calibrated artefact appropriately within the working volume of the CMM
- Use the measurement strategy to take measurements of the real feature on the calibrated artefact
- Compute the associated feature corresponding to the real feature on the calibrated artefact
- Remove the calibrated artefact and position the workpiece such that the real feature is in substantially the same position as was that of the calibrated artefact
- Use the measurement strategy to take measurements of the real feature on the workpiece
- Compute the associated feature corresponding to the real feature on the workpiece.

Then, for any parameter p of the associated feature, the assumption is made that the difference between the *certified* value of p for the calibrated artefact and the *measured* value of p for the calibrated artefact is equal to the difference between the *required* (traceable) value of p for the workpiece feature and the *measured* value of p for the workpiece feature. The assumption is reasonable because measurements are being taken on objects in nominally the same position and with the same measurement strategy and thus CMM systematic errors will be essentially identical and cancel out, although CMM repeatability errors will remain. Since three of the four values in this "equation" are known, the required value of p can be determined.

In practice, the master and test artefact would be measured several times in order to minimise environmental effects and the influence of machine drift. The draft standard contains further essential refinements to the basic scheme and the manner in which the resulting uncertainty in the value of p so determined can reliably be estimated.

A restriction of the substitution method is the need for a calibrated master artefact. This restriction can be overcome in some instances by using a *reference CMM*. Such a CMM is a machine which is traceable through full parametric error modelling. Instead of producing a master artefact specifically, any suitable artefact such as a production artefact can be calibrated on the reference CMM and used as the basis for the substitution method. A company (and there are many) which makes use of several CMMs can nominate and establish one of these machines as the reference CMM, and thus provide traceability without carrying out detailed parametric error modelling of all its machines.

2.3.2 *The use of Class 3 artefacts to determine the systematic error behaviour of a CMM*

For Class 2 checking of a CMM, a standard artefact, such as a ball-plate is measured in a number of positions and estimates of parametric errors are derived from an analysis of the measurement data. This subactivity addressed the problem of determining parametric errors from the measurement of simpler artefacts (termed *Class 3 artefacts*) such as step gauges, plain setting rings (or ring gauges), ball gauges, and spheres.

A mathematical measurement model was established, variants of which cover all these Class 3 artefacts. An approach based on this model for estimating the parameters in the parametric error model of the CMM was developed in a manner comparable to that used for Class 2 checking. As with the Class 2 method, calibration information can also be added. The software developed for processing the Class 3 data is very flexible in terms of its ability to treat any prescribed measurement strategy. It is also modular in that it is capable of ready extension to other Class 3 artefacts by the addition of the appropriate variant of the model for that artefact.

The above approach and supporting software were used to investigate the extent to which measurements of Class 3 artefacts can be used to obtain estimates of the error-correction parameters as in a Class 2 experiment. The experiments indicate that Class 3 measurements can indeed be used to form a basis for the determination of a systematic error model of a CMM in that the measurements lead to systems of equations that can be solved. More importantly is to derive quantitative estimates of how accurately the parametric errors have been determined in terms of their statistical uncertainty. The numerical simulations showed that it is possible with well designed measurement strategies to determine accurate estimates of the parametric errors from measurements of ball gauges, ring gauges and spheres. It should be emphasised that the measurement strategy is quite crucial. As in the case of Class 2 checking, two measurement strategies that at first sight seem roughly equivalent can produce markedly different results.

2.3.3 *Determination of the systematic error behaviour of a CMM by the fusing of Class 3 and Class 2 measurements*

An approach and supporting software were developed to demonstrate how measurements obtained from a Class 2 experiment, regarded as part of a *periodic reverification* of a CMM, may be incorporated or "fused" with measurements from a Class 3 experiment, regarded as part of more frequent *interim checking* of the CMM. As an *adjunct* to Class 2 measurements, the introduction of Class 3 measurements is beneficial in at least three respects:

- In the absence of CMM drift, additional stability can be expected in the parametric error model of the CMM, and the model parameters themselves can be expected to have reduced uncertainties as a consequence of the greater variety and redundancy of measurement data

- As part of interim checking of the CMM the Class 3 measurements contribute to an up-to-date statement of the capabilities of the CMM.
- Measures can be used to assess the extent to which the systematic error model computed from both Class 2 and Class 3 measurements compares with that determined from Class 2 measurements alone taken at the most recent periodic reverification. Significant differences in the measures suggest drift in the error behaviour of the CMM. Thus the regular taking of Class 3 measurements and their use with the most recently taken Class 2 measurements can be used as the basis for deciding when the next full Class 2 check should be made.

The measurement strategy for the class 3 measurements is again very important. For example, it is possible to design a sequence of class 3 checks involving measurements of a ball gauge with the ball gauge placed in a different position at each check in such a way that any systematic change in CMM behaviour will be detected.

Of particular interest is the fact that 1-dimensional artefacts such as a ball gauge can be used to determine accurate estimates of CMM parametric errors. It is therefore possible in principal to use the large reference artefact (Section 1) to determine the parametric errors of a large CMM.

2.4 COMPARISON OF CLASS 2 AND CLASS 3 TECHNIQUES

A CMM can be evaluated using Class 2 techniques or Class 3 techniques. This aspect of the work is concerned with the comparison of these techniques. The work carried out consisted in comparing the techniques with respect to their ability to:

- determine the behaviour of the CMM,
- provide activity-specific uncertainties.

A further subactivity involved developing a methodology for testing software used in Class 2 checking.

The work on each of these subactivities is now summarised.

2.4.1 *Comparison of the techniques in terms of their ability to determine CMM behaviour*

In comparing Class 2 checking (involving a ball plate) and Class 3 checking (involving common calibration artefacts) a number of factors need to be considered, including:

- Resources required to construct the artefact.
- Range of CMM working volumes for which the method is applicable.
- Resources required to maintain (and transport) the artefact.
- Resources required to calibrate the artefact.
- Stability of the calibration information.
- Resources required to measure the artefact.
- Resources required to analyse the measured data.
- Accuracy of the computed estimates of the parametric errors.

The main conclusions are:

- Any method will need to give an adequate sampling of the CMM's working volume if accurate estimates of the parametric errors are to be determined. Thus any method will involve significant measurement resources.
- Any method will have to use three or more probe offsets if all the parametric errors are to be determined. The use of a star-probe is appropriate.
- Ball plates and ball gauges provide a method of determining accurate estimates of the parametric errors.
- The accuracy of the ball plate/gauge method is partly due to fact that the artefact determines rigid 3-D information. However, this information is derived from the measurements of spheres, relatively expensive in terms of measurement time. The usability of these methods could be enhanced if the 3-D information could be provided more cheaply through the measurement of cylindrical dowels, steps with flat orthogonal faces or other approaches.
- Self-calibration methods largely eliminate the need for expensive calibration of the artefacts.
- Ring gauges and spheres provide a method for the determination of the parametric errors in a small or modest volume. They could offer advantages over ball plates/gauges in systems where the measurements can be taken quickly (in scan mode, for instance).
- The type and design of a check depends on a range of factors and it is generally impossible to say in advance which approach is "best" for any particular combination of CMM and type of measurement activity. Comprehensive numerical simulation tools can quickly guide the user to develop measurement strategies to meet the specific requirements.

2.4.2 *Comparison of the techniques in terms of their ability to provide activity-specific uncertainties*

The section above considers the extent to which Class 2 and Class 3 method can be used to determine parametric errors accurately. However, to determine the uncertainty associated with a specific measurement activity does not in general require complete knowledge of the parametric errors: this is the basis of the comparator principle described above. A master artefact having comparable properties to that of the workpiece of interest is measured and the workpiece feature itself is measured according to the procedure provided. The measurement uncertainties are estimated in the manner detailed in that procedure. Thus the comparator principle is a way of deriving activity-specific that does not require the determination of the CMM parametric errors.

If reliable estimates of a CMM parametric errors are known (through the measurements of Class 2 artefacts, say,) then, in principle, the uncertainty of *any* measurement activity can be estimated using a numerical simulation of the CMM – the *virtual* CMM (VCMM). The design and use of the VCMM is considered in detail in Section 4.

The comparator principle also applies in cases of fusing data from Class 2 and Class 3 checks. Suppose that a reasonably accurate estimate of the parametric errors are available but that for a particular measurement task additional accuracy is required. The measurements of an appropriately calibrated master artefact can be fused with the Class 2 checking data to produce an update to the parametric errors that have increased accuracy for the measurement task in hand. For example, if measurements of a step gauge are incorporated in a Class 2 check, the uncertainty of distances between points lying approximately on the measurement line for the step gauge will be reduced.

2.4.3 *Methodology for testing software used in Class 2 checking*

The determination of estimates of CMM parametric errors from measurement data is a difficult computational problem and it is important that software used to perform these computations is operating reliably. An effective method of testing software is to run the software on reference data and compare the results output by the software under test with reference results calculated *a priori*. The approach depends on being able to produce reference data and corresponding reference results. One method is to generate data, apply *reference software* to the data and regard the output data as the reference results. Obviously for this strategy we need reference software and for the Class 2 checking problem the software described above as can be regarded as a reference implementation. The comparison of the results produced by test software under test can be on the basis of the parameter values or the error function values.

The methodology has been used to test a number of estimation methods published in the literature. The results show that these methods introduce significant bias, even for well-

designed measurement experiments.

2.5 OPTIMUM PROBING STRATEGIES

The aim of this activity is to find the best ways of distributing the measurement points on a workpiece feature in order to deduce properties of the feature. The accuracy and effectiveness of co-ordinate measurement depend on the CMM operator probing the feature in a sensible way. The work carried out consisted of four main subactivities:

- Mathematical modelling, numerical simulation and experiments to determine optimal probing strategies for standard and Class 3 artefacts
- Development of guidelines for probing strategies for a range of artefacts
- Collection of measurement data for industrial artefacts
- Design numerical simulation software

Note: Here the term form error is taken to mean the departure from perfect form with respect to position. For instance, the form error for a section of a nominally cylindrical shaft is a function which is often sinusoidal with respect to angle subtended by points on its profile. In contrast, the term *maximum form departure* denotes the largest value of (the magnitude of) the form error. In the case of the cylindrical section, the largest value of (the magnitude of) the form error along the profile would be taken.

The work on each of the above activities is now summarised.

2.5.1 *Mathematical modelling, numerical simulation and experiments to determine optimal probing strategies for standard and Class 3 artefacts*

In measuring a real feature on a workpiece, the operator must decide the probing strategy that will deliver measurements from which the various parameters of the computed associated feature can be determined to the required accuracy. The key questions are:

- How many points on the feature should be measured?
- How should these points be distributed over the feature?

The “required accuracy” usually relates closely to tolerancing requirements. In comparing computed parameter values with design tolerances it is necessary that the former are known to have standard uncertainties that are no greater than one tenth, say, of the width of the

appropriate tolerance bands.

This work focuses on providing a means by which the operator can obtain this essential information. Currently, many measurements are made with little underpinning information on whether at one extreme they are adequate or at the other wasteful for the measurement activity. The use of an arbitrary number of measurements in arbitrary position can at worst lead to a measurement result with incorrect values and misleading uncertainty. An example is the measurement of an artefact containing periodic form error; measurements which coincide only with the peaks or with the valleys will give a false impression of the size of the feature and of its form.

For any one particular workpiece feature, no one probing strategy is universally applicable. The reasons are primarily that

- The form errors on the feature depend on the method of manufacture of the workpiece
- The feature may be “incomplete”, e.g., it may be hemispherical, say, rather than a complete sphere
- The feature may be “complete”, but it might not be possible to probe all parts of its surface due to access problems.

It follows that a probing strategy must take account of these factors, and the guidelines presented reflect this requirement.

Although no one probing strategy can be universally applicable to all cylinders (for example), it is possible to develop a strategy that applies to all cylinders of a particular specification produced by a particular manufacturing process. The strategy must be more than just a probing strategy, and include monitoring of the stability of the production process to ensure that the current probing strategy remains applicable and if necessary to adapt it.

The approach developed within the project is based on an initial exploratory stage in which more measurements are taken than would normally be considered reasonable in industrial production, in order to ‘learn’ about the properties of the feature. These measurements are analysed to determine an efficient routine inspection strategy which meets the tolerance assessment requirements. It would be necessary to repeat periodically the larger number of measurements in order to validate the decided sampling strategy or to re-design it if necessary.

The starting point is the observation that if the precise form error of the workpiece feature were known then it would be possible to place the measurements in such a way that this form error can fully be accounted for. The resulting associated feature and the form error so deduced could be taken as reliable estimators of the real features and the real form error. In particular, the maximum form departure could be compared with design tolerances to determine whether the real feature met specification. In practice, because probing strategies

are often inadequate, the form error so deduced would be an *underestimate* of the real form error. It is necessary to take account of this fact in comparing its value with tolerancing information. One way in which this is often done in practice is to allow a sufficiently generous margin in making the comparison. The approach outlined below permits this margin to be quantified.

The approach involves the realistic estimation of the form error by initially taking a large number of measurements of the feature of concern on a typical workpiece or several typical workpieces and processing them appropriately. This number would normally be such that if it were to be used for production purposes it would be uneconomically large. From this information, the effect of taking a smaller number of measurements can be deduced. In particular, the extent to which the computed parameters of the associated feature and the form error so estimated depart from the more reliable values based on a large number of measurements can be determined. Further, expected and worst-case underestimation factors can be produced. These factors are used to inflate appropriately the maximum form departure determined from the "realistic" number of measurements and thus mimic the value that would be achieved using the large number of measurements. By this means the above-mentioned margins are quantified.

The process can only be expected to operate satisfactorily if the manufacturing process and the measurement system remain stable. As indicated above, this can be tracked by taking large numbers of measurements of the feature concerned on a periodic basis.

2.5.2 *Development of guidelines for probing strategies for a range of artefacts*

The above approach leads to a guideline applicable to a wide range of workpiece features. In any particular case, the following steps should be carried out:

1. Decide a class of "nested" measurements strategies for the workpiece feature of concern

Example: In measuring a section of a cylinder the class could be 5, 10, 20, 40, 80, and 160 uniformly-spaced points on the section, where the locations of each set of points is contained within the next set. Thus, if the five points were in angular positions 0, 72, 144, 216 and 288 degrees, the ten points would be at 0, 36, 72, 108, 144, 180, 216, 252, 288 and 324 degrees.

2. Take measurements on the required feature of a representative workpiece according to the largest number of measurements in the class of measurements strategies. Ideally, repeat these measurements for different representative workpieces, so that the degree of variability can be estimated.

Note: The measurements need not be taken with the CMM that would

subsequently be used for production purposes. They should, however, be taken with a measuring instrument that operates to sufficient accuracy.

Example. For the above cylinder example, take 160 uniformly-spaced measurements on the section.

3. Fit the appropriate associated feature to these measurements.

Example: For the cylinder example, fit a Chebyshev circle to the measurements.

4. Take the residuals of the associated feature as a discrete description of the form error.
5. For this representation of the form error, estimate the expected and worst-case underestimation factors for any choice of number of measurement points.
6. From these underestimation factors, select a number (and locations) of measurement points that gives an acceptable balance between the economy of measurement and an acceptable margin in checking against design tolerances.

2.5.3 *Collection of measurement data for industrial artefacts*

Measurements were taken of a range of laboratory and industrial artefacts. As an example, measurements were taken by collaborator GKN Technology of various features on constant velocity joints (CVJs). Such joints are the main drive-line component in front-wheel-drive mechanisms and are required to be manufactured and measured to demanding accuracies. The features measured included various track forms of the inner and outer races and cages of CVJs. These forms comprise sections of spheres or ellipsoids of revolution which are nominally arcs of circles or sections of more complicated surfaces which are nominally Gothic Arch in character (a composite curve consisting of a *pair* of circular arcs).

Measurements were taken with Talyrond and Talysurf instruments, thus providing not only a much larger number of measurements than would normally be obtained with a CMM, but also to high accuracy. Thus form error was identified clearly in the measurements as a consequence of this accuracy.

For each measurement set the following steps were carried out:

- The nominal shape (associated feature) was determined and subtracted from the measurements to give a sequence of residuals which would form the basis for describing the form error (with respect to position) of the measured features.
- A piecewise linear interpolant of these residuals was used to provide a functional representation of the form error in terms of position along the measured profile.

Note 1: In this case the measurement error is small compared with the form error, and hence it is satisfactory to interpolate the residuals. In cases where this is not so, it would be necessary to fit the residuals by a suitable approximating function such as a polynomial spline.

Note 2: A piecewise linear interpolant is suitable because there is a large quantity of closely spaced data. In cases where this is not so, an interpolating (or approximating) function of higher order would be required.

- The difference between the maximum and minimum values of this function (equivalent in this case to the difference between the maximum and minimum residuals) was taken as the actual maximum form error.
- By sampling from this function using different sampling rates, the effect of various measurements strategies was assessed.

2.5.4 *Design of numerical simulation software*

Numerical simulation software was designed for carrying out the functions implied by the above description. Its constituent parts are

- the fitting of the appropriate associated feature to the measured data
- the application of interpolating or approximating functions to fit the residuals of the associated feature and hence provide a representation of form error as a function of position
- the determination of the maximum form error from the difference of the maximum and minimum values of this function
- the sampling of the form-error function at various sampling rates to simulate the effect of different measurement strategies
- the determination of the strategy-dependent maximum form errors from the differences of the maximum and minimum values of the sampled function for the various sampling rates
- the determination from this information of expected and worst-case underestimation factors for the various sampling rates

2.6 SUMMARY

The following summarises the main conclusions and recommendations.

- 1 CMM parametric errors can be described successfully by kinematic and empirical models.
- 2 Kinematic models are restricted to CMMs whose behaviour can be described by an axis-upon-axis build-up. For this class of CMM (the majority), they represent an efficient description of behaviour.
- 3 Empirical models are capable of describing more general repeatable CMM behaviour.
- 4 It is possible to design and implement Class 2 checking software based on a comprehensive model of a Class 2 checking experiment that gives unbiased estimates and is totally flexible and extendible.
- 5 Reliable estimates of uncertainties of parametric errors can be derived from Class 2 measurement data.
- 6 Class 2 experiments which incorporate self-calibration strategies give more accurate estimates of parametric errors and vastly reduce the need for additional calibration information.
- 7 Class 2 experiments should incorporate a validation phase.
- 8 Measurement strategies for Class 2 checking can be designed using numerical simulation software.
- 9 Measurements of Class 3 artefacts such as plain setting rings (ring gauges) can be used to determine CMM parametric errors.
- 10 The substitution or comparator principle can be used for activity-specific measurement when an appropriate master artefact is available.
- 11 Measurements of a Class 3 artefact can be used to update and improve the parametric error model obtained from a Class 2 check. The additional information should enable the model to be made more reliable and realistic and, because of the greater data redundancy, to have smaller uncertainties associated with it. The relative simplicity of Class 3 measurements permit inexpensive and adaptive updates of the model to be made on a regular basis. Software is available for this activity.
- 12 The time interval between Class 2 checks can be controlled by the behaviour of certain measures of consistency derived from measurements of Class 3 or Class 4

artefacts.

- 13 A general methodology for determining probing strategies has been developed that takes into account likely form error and tolerance requirements.

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3 OPERATING CONDITIONS AND SAMPLE HANDLING

3.1 INTRODUCTION

Section 2 of this report concerned the CMM measurement errors that arise as a result of imperfect geometry – the parametric errors. The geometry of a CMM can also be influenced by two further factors, thermal environment and sample loading and these are considered in this section.

When it is calibrated by a manufacturer, the CMM is normally sited in as perfect a uniform temperature distribution as possible. In practice, however, such uniform temperature conditions can rarely be achieved. Hence in non-ideal temperature conditions, various parts of the CMM will distort and co-ordinate measurement errors due to:

- changes in the ambient temperature
- spatial temperature gradients

- temporal temperature changes.

A number of experimental investigations into the effects of temperature on the accuracy of CMM have been undertaken in various National Measurement Institutes in Europe. In general, such investigations fall into two categories, i) finite element analysis using complex models of CMMs, or ii) investigation of the thermal characteristics of a specific CMM. There is very little practical guidance to the CMM user on simple cost-effective techniques to improve CMM performance in an industrial environment. Clearly, CMM users could be advised simply to house their CMMs in temperature-controlled environments. However, the trend is to use CMMs on the production line and this option may be difficult in many cases. There is also other obvious advice that could be given, such as shielding the CMM from strong draughts, and avoid siting the CMM in direct sunlight and other sources of thermal radiation. Alternatively, CMM users could be advised to monitor the effects of temperature by measuring the apparent changes in the dimensions of components that were manufactured from materials with very small thermal expansivity. However, without a means of analysing the results of such measurements these may be difficult to interpret.

Vibration and air purity are among the other environmental factors that have an influence on CMM performance. Information on these problems, when related specifically to CMMs, are referred to in very general terms only in some USA standards. For example, the influence of vibration is specific to a particular location and the vibration-isolation system installed on the CMM.

When considering the sources of error associated with co-ordinate measurement it is also necessary to consider the influence of the workpiece on the CMM. In the simplest case, the effect is the mechanical bending of the geometry-defining elements of a CMM.

An investigation of the influence of thermal effects on a CMM by a series of case studies was undertaken in order to provide CMM users with a series of bench-mark examples and describe the effects of undertaking a series of simple modifications to the thermal environment. For example, tests on a variety of CMMs in different thermal environments formed two distinct groups:

- CMMs operating in a well-characterised environment that could be varied in a well-controlled way, or
- CMMs operating in a range of thermal environments so that the effects of different thermal conditions on the CMM itself and the components under test could be assessed separately.

Both approaches were regarded as important to provide the broadest view of the problem.

Similarly, practical approaches were needed to investigate the effects of sample loading on CMM behaviour.

Thus, in order to develop guidelines for operating conditions, the following activities were undertaken:

- quantify the effects of thermal influences in a range of thermal environments,
- quantify the effects of sample loading.

These activities are now summarised.

3.2 THERMAL INFLUENCES ON THE CMM AND THE COMPONENTS UNDER TEST

A number of approaches for investigating thermal influences were considered, including:

- Arrange a multiplicity of sensors on a particular CMM. The measurement data from the sensors is then applied to a thermal model of the CMM so that predictions of CMM performance against a known thermal environment can be made using finite element analysis techniques;
- Measure the dimensions of features on an artefact such as a ball-plate or hole-plate manufactured from material with a very small thermal expansivity. The differences between the co-ordinates of the features on the plate, when measured under different sets of temperature conditions, could be used as the basis for calculating the changes in the CMMs geometry for the particular change in temperature conditions.
- Improve the thermal environment in the vicinity of a CMM, for example covering the CMM with insulating material, or shielding the CMM from radiation.
- Analyse the performance of CMMs with temperature compensation.
- Apply finite element analysis software to provide order of magnitude estimates of the thermal characteristics of a wide range of engineering components.

Although the use of many temperature sensors is too specific for most industrial CMM users, it can be considered a good technique for a specific CMM where the very best results are required in a difficult thermal environment.

A number of case studies were carried out in order to determine quantitative information about thermal effects based on:

- ISO 10360-2 and plain setting ring tests
- Measurement of acclimatisation times for artefacts.

3.2.1 ISO 10360-2 and plain setting ring tests

A comprehensive series of tests were carried out by a collaborator in the project who has a Leitz PMM 866, a CMM with a fixed portal and a moving table with temperature compensation facilities. Its length measurement capabilities as specified by ISO 10360-2 are $\pm (0.8 + L/400) \mu\text{m}$. The experiments covered:

- Diagonal measurements of a step gauge, before and after service
- ISO 10360-2 test in a good environment with and without temperature compensation
- ISO 10360-2 test in a poor environment with and without temperature compensation
- Plain setting ring tests in a good environment with and without temperature compensation
- Plain setting ring tests in a poor environment with and without temperature compensation

The main conclusions from the experiments were:

- Operating in a good thermal environment, applying temperature compensation based on a simple linear model did not improve significantly the performance of the CMM.
- Operating in a poor thermal environment, temperature compensation is of significant benefit.
- Operating in a poor thermal environment caused the CMM geometry to distort.
- Comparing the ISO 10360-2 and ring measurements, it was seen that the errors in the estimates of the ring diameter were more than that estimated from the length measuring capability as determined by the ISO 10360-2 test. For this case at least, the ISO 10360-2 test underestimates the machine errors.

3.2.2 Acclimatisation times for artefacts

Acclimatisation times of artefacts were studied by experimental methods and by finite-element modelling. Two types of artefact, with different material and thermal properties, viz., aluminium-alloy and hardened-steel gauge blocks, were used, each supported in two different ways. One method of support was on rubber blocks, for which convection effects are dominant, and the other was directly on an aluminium plate, for which conduction effects dominate.

For the experimental tests, the temperature difference between the artefact and the

surroundings was monitored at frequent time intervals using a thermocouple attached to the centre of the artefact and five additional thermocouples in the surrounding air and on the plate. For the modelling approach, a finite-element software was used. The artefact and the plate were modelled by suitable elements and the package provided with the material and thermal properties (thermal conductivity, specific heat, density and the coefficient of thermal expansion) of the aluminium alloy, the hardened steel and the rubber blocks. The experiments examined:

- Heat loss by convection, in the form of an empirical formula for heat flux as a function of
 - Artefact dimensions
 - Artefact orientation
 - Temperature difference from ambient air
- Heat transfer due to radiation, in the form of a formula and a table.

From these experiments, settling times, in the form of a look-up table giving the temperature difference from ambient at which the artefact will not change any more in length than an input length-tolerance value, were derived.

3.3. SAMPLE HANDLING AND LOADING

The following work was carried out in developing guidelines for sample handling and loading.

The influence of the weight and weight distribution of the components on the accuracy of a particular CMM was explored. An approach was developed which involved:

1. Selecting a *test weight*, appropriate for the CMM, on the machine,
2. Performing a probe check as described in the standard both in the presence and absence of the test weight on the machine,
3. Performing a sequence of measurements of length standards artefacts both in the presence and absence of the test weight on the machine
4. Checking whether the range of readings in Steps 2 and 3 lie within the stated volumetric performance specification of the machine.

The result of this work is a technical guideline, a copy of which is provided at the end of this section. It is expected that this guideline will be published by ISO with only minor amendments. The guideline has been tested in an industrial environment at Caterpillar in the USA.

4 GRADING SCHEME: THE VIRTUAL CMM

4.1 INTRODUCTION

The fundamental consideration for the CMM user in choosing a CMM is whether it will measure parts to the accuracy required. One factor in driving this requirement has been that neither ISO 10360-2 nor BS 6808 contain information relating to task-specific uncertainty statements. The objective of this part of the work is to provide a method of grading CMM performance that is applicable to a wide range of measuring activities.

To achieve a really simple grading system it would be necessary to create a system within which claims like "the CMM can measure all geometrical features to an accuracy of $x \mu\text{m}$ in accordance with specification standard ISO 123456" could be made. This approach would be in line with the currently used concept where the performance of a CMM is stated in terms of the capability of the CMM to measure a length standard placed arbitrarily within the working volume of the CMM in accordance with ISO 10360-2.

For a particular CMM the uncertainty for making length measurements might be (at worst) $5 \mu\text{m}$, but the uncertainty for measuring the diameter of a sphere (within a certain range of dimensions) could be $8 \mu\text{m}$ and the uncertainty when measuring the dimensions of a cylinder (within some range of dimensions) might be $30 \mu\text{m}$. A further complication is that since CMMs are frequently used to measure angles, in order to provide the user with information on the CMM's ability to measure angle another figure of merit might be needed – consequently adding to the complexity of an initially simple concept. Thus, it is evident that there is no simple route to provide a universal grading system.

A major difficulty with activity-specific measurement uncertainties is that the raw CMM measurements alone do not provide information from which uncertainties can readily be deduced. Indeed, even to compute fundamental quantities such as the diameter of a cylinder requires several key decisions to be made:

- The number of measurements to be taken on the (nominally) cylindrical feature
- The placement of these measurements
- The method of processing this measurement data to compute the diameter, implying:
 - The choice of associated feature (in this case a Gaussian, Chebyshev, minimum circumscribed or maximum inscribed cylinder).
 - The application of appropriate software for fitting this associated feature.

Following these stages, it is then necessary by some means to estimate the uncertainty associated with the computed diameter.

A general way of predicting the uncertainty of a clearly stated measurement, e.g., the uncertainties associated with measuring a cylinder or sphere for a specified measurement strategy, has to be established before progress can be made. Without a sound basis for establishing uncertainty statements there would be considerable risk of misleading users of CMMs with erroneous estimates of a CMM's capabilities. Furthermore, CMM manufacturers would have justifiable concerns if the proposed methods were not thoroughly underpinned by good metrology and sound theory.

One approach is for a potential CMM user to take an artefact, similar in design to the components being tested, to several different manufacturers and compare the measured results. Ideally, a calibrated artefact would be used to provide traceability to the metre. For some users this would be an entirely adequate procedure. However, for the vast majority of users this approach is very limited in application and more general tests or figures-of-merit are needed.

Three main options were considered.

The first option involved the development of algorithms based on the simplest possible description of the accuracy of a CMM. For example, if the spatial error of the CMM, as stated by the manufacturer, were 5 μm , then using this value the uncertainty when the CMM was measuring the diameter of a cylinder (within a range of dimensions, and using a suitable measurement strategy) might be 10 μm or 15 μm , depending on the particular type of CMM. This method is likely to give rise to serious under- or over-estimates of the error of measurement, especially when large geometric errors are present in the CMM. For example, it is possible for a co-ordinate measuring system to measure any length within its working volume accurately but still have large parametric errors.

The second option involves the development of a range of standard artefacts which the CMM manufacturers would use to report the accuracy of their CMMs. These would be costly for individual manufacturers to hold and their calibration would be expensive, because a very wide range would be required to cover all cases. Achieving a consensus on the choice of the full range of artefacts would be difficult. The approach also requires being able to interpolate or extrapolate from behaviour on a finite range of artefacts to the activity in hand and there seems no reliable or manageable way of doing this.

The third option is based on the actual measurement activity and does not call for any extrapolations. An obvious way to assess the ability of a CMM to measure a particular workpiece feature is first to measure the feature repeatedly in a wide range of positions with different measurement strategies within the working volume of the CMM. Then, by fitting the appropriate associated feature to each such set of measurements and examining the range of feature parameters (diameter, angle, etc.) obtained, a reliable indication of the variability of these parameters can be deduced and measurement uncertainties estimated. This approach would not necessarily detect systematic errors such as a global scale error. A variation is to replace the workpiece by a master artefact of the same design and use the calibration

information associated with the master artefact to detect systematic errors as well as the variation in performance. This is essentially the comparator principle generalised to account for different measuring procedures. Although this form of assessment could prove to be an extremely useful exercise (and is implemented for very common measurement activities), it is exorbitant in its usage of CMM time and therefore usually prohibitive.

However, given a 'virtual' CMM (VCMM) that can faithfully simulate the CMM's behaviour, any number of measurement experiments varying artefact dimensions, shape, measurement strategy, probe selection, etc. The VCMM provides the simulated measurements, from which the uncertainties of the associated features (cylinders, cones, etc.) corresponding to these points for each position of the feature can be deduced. This approach requires a higher level of mathematical modelling, but represents a once-only investment and is less likely to provide the user with a misleading picture of a CMM's ability to perform a measuring activity.

The aims of this part of the project were to:

- develop and use a virtual CMM to simulate faithfully a CMM, and
- to devise and use a sufficiently flexible methodology to permit activity-specific uncertainties for any measurement activity that could be carried out on the actual CMM to be reliably estimated.

4.2 PREDICTING MEASUREMENT ERRORS WITH ANY CMM FOR ANY MEASUREMENT ACTIVITY

The work carried out consisted of four subactivities:

- Development of a mathematical model of CMM behaviour taking into account probing configurations.
- Development of a framework for defining and interpreting uncertainty statements for measurement activities.
- Development of a virtual CMM software system to simulate CMMs with known parametric error and probing configurations.
- Simulation of measurements of standard and Class 3 artefacts by CMMs with known parametric errors and comparison with actual measurements

The work on each of these subactivities is now summarised.

4.2.1 *Development of a mathematical model of CMM behaviour taking into account probing configurations*

Models for CMM behaviour which describe the parametric errors are described in section 2 and its supporting documentation. The main work in this subactivities was to develop or extend models to describe the systematic errors associated with the operation of the probe. This resulted in a combined model summarised as $x^* = x + e_m(x, a, p) + e_p(n^*, b, p) + \varepsilon$ where:

x^*	are the coordinates of the true position of the point of contact between the workpiece and the probe tip,
x	are the recorded scale readings for a fixed point within the probe housing,
$e_m(x, a, p)$	describes the systematic error behaviour of the CMM, depending on scale readings x , model parameters a and the probe offset p that gives the nominal position of the centre of the probe tip in relation to the fixed point within the probe housing,
$e_p(n^*, b, p)$	describes the systematic error behaviour of the probing system, depending on the outward normal n^* to the workpiece at the point of contact, model parameters b and the (nominal) probe offset p , and
ε	has components that are samples from a Gaussian (normal) distribution that describe the random error behaviour.

An important aspect of the model is that the parametric error model (PEM) and the probe parametric error model (PPEM) occur additively and can be defined independently of each other.

A comprehensive model for a general touch-trigger probe system was developed which took into account:

- the kinematic errors associated with the imperfect motion of the probe
- stylus orientation
- stylus length
- contact angle
- lobing and tilt errors

as well as methods and procedures for characterising a probe conforming to the model from measurements of artefacts.

The behaviour of accurate analogue probes can be approximated as having random

measurement error. The work established a framework into which the analysis of the behaviour of other probes can be placed.

4.2.2 *Development of a framework for defining and interpreting uncertainty statements for measurement activities*

In order to determine whether a CMM is fit for a measurement activity, there needs to be some concrete way of comparing the CMM's performance with the requirements. A general framework was developed for doing just this in a natural way that takes into account not only the tolerance requirements but also the measurement strategy used. The approach can be illustrated with simple example.

Suppose the activity is to determine the radius of a circular artefact of nominal radius 50 mm by determining the radius of the least squares best-fit circle to measured data points to an accuracy of better than ± 0.005 mm. A practical approach would be to take a plain setting ring (ring gauge) with a calibrated radius of 50 mm, measure it with the CMM, calculate the radius of the best-fit circle to the resulting data measurement data. If the calculated radius lies well within the tolerance band, then the CMM *and* the specified measurement strategy are fit for this activity. This approach can be generalised in other tolerance assessment activities.

4.2.3 *Development of a virtual CMM software system to simulate CMMs with known parametric error and probing configurations*

A comprehensive, open and extensible, virtual CMM software system has been developed. It has a two main functions. In the first stage, measurements of an artefact taken by a perfect CMM (using a perfect probe) according to a specified measurement strategy are converted into the corresponding measurements that would have arisen if a CMM with specified imperfect geometry and probing errors has executed the same measurement strategy. The second stage applies specified tolerance assessment software to both sets of data and compares the results for the perfect and imperfect CMMs. In this way, *the accuracy of any CMM, characterised in terms of its parametric and probing errors, can be assessed for any measurement activity.*

The VCMM has modules for:

- generating data lying exactly on an artefact, with or without form error. These are regarded as the points of contact for the measurements. The software also calculates the normals to the surface of the artefact.
- calculating the scale readings associated with the points of contact for a perfect CMM.
- calculating the scale readings associated with the points of contact for a CMM with

specified parametric and probe error behaviour. These use functional iteration to solve the sets of 3×3 nonlinear equations that arise.

- for estimating the point of contact from scale readings. This is important in quantifying the errors that occur in making simplifying assumptions in these calculations.
- performing a wide range of tolerance assessment activities.
- comparing scale readings and estimates of the points of contact with their true values.
- generating random perturbations with a specified covariance matrix. These can be used, for example, in perturbing the parametric errors according to the covariances determined from a Class 2 experiment (Section 2).

The system is open and extensible in the sense that any parametric and probe error model can be catered for through the use of fixed interfaces. Kinematic and empirical parametric error models (including linearised versions) and the kinematic probe error models have been implemented. Similarly, any tolerance assessment software can be incorporated and a wide range has been implemented including

- Gaussian (least squares) substitute elements,
- Chebyshev substitute elements, including maximum inscribed and minimum circumscribed, elements where appropriate,
- Gaussian and Chebyshev profile and template matching,
- Part mating for multiple components.

The VCMM system provides the user with a wide range of tools in an easy-to-use format to build a simulation of a measurement activity. The system can be used in different modes to address different problems such as:

- Determine if CMM A is fit for performing tolerance assessment activity *a* using measurement strategy *X*.
- Determine a measurement strategy *X* to address tolerance assessment activity *a* using CMM A.
- Determine the accuracy that can be achieved by a CMM in performing assessment activity *a*.
- Determine if a measurement strategy is effective in detecting (specific types of) parametric errors.

4.2.4 *Simulation of measurements of standard and Class 3 artefacts by CMMs with known parametric errors and comparison with actual measurements*

A range of template numerical experiments have been performed to investigate the factors affecting the accuracy of CMM measurements, including

- sampling strategy: number and distribution of the data points on the artefact's surface,
- position (location and orientation) of the artefact within the CMM working volume,
- nature of the CMM parametric errors.

The system will be commissioned for a service operated through the Co-ordinate Metrology Association to determine activity specific uncertainties for users.

4.3 GRADING CMMS - CONCLUSIONS DERIVED FROM THE WORK

One aim of this project has been to determine whether it were possible to grade CMMs according to some measure of their real or predictable "measuring capability". The major difficulty in attempting to quantify any parameter of this sort is that because a CMM is so versatile it is more or less impossible to produce a unique way of grouping complex characteristics together into one "figure of merit". Nevertheless, there are two approaches considered here that could form basis of some more practical approaches.

The "qualitative" approach. In general, the level of complexity of a CMM is reflected in its price and hence in the features in its technical specification. Therefore, it would not be unreasonable to group, or grade, CMMs according to some key features. The main key features would be:

- Performance in accordance with ISO 10360-2
- Validated software
- Temperature compensation
- Geometrical error compensation

There may be other features which may be relevant, but at the next level of detail there are likely to be long debates between manufacturers as to what is important and what is not. Even at this relatively simplistic level, it is the case that there are several high-quality CMMs which are able to achieve reliable high-accuracy measurements without the need for geometrical error compensation. Moreover, provided a CMM is housed in a reasonable thermal environment, the performance of some CMMs, as has been shown in this project, are not enhanced by thermal correction. Indeed, for some applications there may be arguments for not applying such corrections. It is possible, for example, for there to be a quantised error introduced by a temperature sensor with insufficient resolution causing a significant change

in the co-ordinate data collected which would not be present when the sensor was not used to correct the data.

The "quantitative" approach. The performance of a CMM as specified in ISO 10360-2 does provide a limited indication of a CMM's ability to measure length. Strictly speaking, the ISO 10360-2 procedure is a sampling process in which perhaps only 60-80% of the maximum possible error is revealed. (It is worth bearing in mind that the main purpose of the performance verification method specified in ISO 10360-2 was to enable users to compare CMMs on a "like-for-like" basis.) As indicated above, there can be no simple algorithm to enable the transition from the length measurement statement to a CMM's ability to measure a cone or a cylinder (since there are models of CMM behaviour that deliver exact length measurements but still have large geometric errors). The ISO 10360-2 approach can be extended to include other measurement activities since any such performance indicator can be used as long as the performance of all the CMMs reviewed is judged on the same basis. Frequently, work pieces provide the synthesis of the elements of most interest to the user. Therefore, it would seem very sensible for the user to use such parts as the transfer standard between CMMs, *provided that the part was known to be dimensionally stable*. This requirement is particularly important in the case of the higher accuracy CMMs, where the dimensional stability of a typical part is often comparable with, or worse than, the repeatability of the CMM! However, the general approach has the limitation that it is more or less impossible to extrapolate the behaviour on a collection of artefacts to a new type of artefact.

The virtual CMM provides a mechanism to assist not in providing a single figure of merit for a CMM but in giving a practical means for assessing suitability of the CMM for a specific measurement activity or set of measurement activities. It is able to do this through the use of models of CMM and probe behaviour and it is valid as long as these models are valid. The kinematic models described in Section 2 have long been accepted by researchers as an adequate description of the repeatable behaviour of a large class of CMMs. The more general empirical models developed by NPL can extend their applicability further. In order to apply these models in practice, it is necessary to determine accurate estimates of the parametric errors for particular CMMs. This project has considered Class 2 and Class 3 techniques for doing precisely this. It has also addressed probe error models and validation. With these components now in place, the virtual CMM is set to become an important tool in assessing uncertainty in coordinate metrology.

4.4 SUMMARY

The following summarises the main conclusions and recommendations that arose from the execution of this activity.

- 1 Mathematical models of CMM parametric and probe errors covering a large class of CMMs have been developed.

- 2 A framework for the expression activity-specific uncertainties taking into account tolerance assessment requirements and measurement strategy has been developed.
- 3 An open and extensible virtual CMM system to model any CMM and any measurement activity has been developed.
- 4 The virtual CMM provides a practical means for assessing suitability of the CMM for a specific measurement activity or set of measurement activities

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ACKNOWLEDGEMENTS

The work presented here was carried out by a project team from NPL and collaborating partners. Their contribution is gratefully acknowledged. Particular thanks go to A J Abackerli, B P Butler, N R Cross, J R Dotson, D R Flack, S A Hannaby and P M Harris. We also thank B J Chorley for a careful reading of a draft of this report. The work reported on here was supported by the National Measurement System Policy Unit, Department of Trade and Industry.