Abstract

In this paper we describe a large reference artefact for use in CMM verification. The artefact is of modular design, constructed in 1 m or 0.5 m tubular sections made from carbon-composite materials. Each section can carry a range of reference surfaces including reference spheres (tooling balls). We discuss the calibration of the artefact using a repositioning methodology and the use of the artefact in CMM verification.

1 INTRODUCTION

A major step in establishing the traceability of measurements carried out by co-ordinate measuring machines (CMMs) involves the comparison of CMM measurements of an artefact with calibration information associated with the artefact. This approach is explicit in ISO 10360-2 [1] which gives a procedure for determining the length measuring capability of a CMM from measurements of calibrated length artefacts such as gauge blocks and step gauges. Although the standard applies most directly to CMMs with operating axes of 1 metre or less, its underlying principles apply to any co-ordinate measuring system working in essentially any volume. To carry out a verification according to the standard requires:

- a reference artefact whose length is no less than 67% of the longest diagonal within the working volume,
- a calibration of the length of the artefact accurate to at least 20% of the accuracy of the CMM, and
- measurements of the length of the artefact along seven distinct measuring lines.
The method is limited only in our ability to provide an artefact that can be accurately calibrated and stably positioned within the working volume. While step gauges and gauges blocks of up to 1 metre, suitably calibrated, are not uncommon, the construction of longer artefacts with comparable accuracy presents significant difficulties. The National Physical Laboratory, UK, (NPL) along with the Centro Espanol de Metrologia, Spain, (CEM) and the National Metrology Laboratory, Ireland (NML) are completing a European project which addresses this problem directly. The main aims of the project are:

- to design and construct a large reference artefact (LRA) which can be up to five metres long, which is structurally stable, easily supported and positioned and is of modular construction for flexibility and ease of portability, and
- to provide a method for its accurate calibration for use in the verification of large CMMs according to the principles of ISO 10360.

In section 2 we describe the design and construction of the large reference artefact and in section 3 we discuss the calibration of the artefact. Section 4 concerns verification of a large CMM from measurements of the artefact and related issues. Our concluding remarks are given in section 5.

2 ARTEFACT DESIGN AND CONSTRUCTION

An early design decision was to build the artefact of carbon-composite materials, thus providing rigidity and at the same time keeping the artefact light–weight. To meet the modularity requirements (and, as we will discuss later, to enable accurate calibration) the artefact is constructed from tubular sections; see Figure 1. For the construction of the tube, the bulk of the fibres are layed uni-directionally and aligned with the tube axis. An additional layer of carbon fibre material is wrapped around the tube at 90° to the tube axis which helps to control the ovality of each individual completed tube. The tubes used for the prototype LRA are 1 m (4 have been made) and 0.5 m (2 have been made) in length. This range of sizes will allow for the verification of the performance of machines with largest dimensions from 1 m to 5 m in 0.5 m steps. It is possible, in principal, to add further sections.

The requirement for modularity introduces the problem of how the modules are to be joined together. For this purpose, each tube has a flange of laminated construction bonded to each end. The flanges are manufactured from sheets of carbon fibre, each laid at a different orientation and pressed over a former, the required thickness being built up in layers. The flanges contain kinematic mounts that allow the modules to be assembled as one long artefact and to be disassembled and reassembled in a highly repeatable way. This creates an immensely strong structure.

There are eight measuring stations on each 1 m-module and four on each 0.5 m-module, mounted axially 125 mm apart, in line with a generator of the
cylinder, the stations are positioned symmetrically such that this spacing is preserved across the joins. The measuring stations are positioned symmetrically such that the 125 mm spacing is preserved across the joins. These stations consist of titanium platforms bonded to the tube and are designed to carry a range of reference surfaces such as steps (gauge blocks), cylindrical dowels or spheres. The complete assembled artefact can hold 40 reference surfaces that can be used to define calibrated lengths associated with the artefact. A cubical ‘base-station’ has been designed and manufactured from titanium to which the tubular sections can be attached. Using this base-station, a reference artefact can be assembled as an L-, T-, V- or X-shaped 2-dimensional artefact or a 3-dimensional artefact of various configurations.

![Image of the artefact](image_url)

**Figure 1.** Two modules of the large reference artefact joined together. Each module is shown carrying eight reference spheres affixed to the measuring stations on the top of each cylindrical section along with four spheres attached to the sides of the sections. All spheres can be used to carry calibration information and to define reference points in repositioning strategies.

The prime function of the artefact is to provide an ultra-stable structure to carry reference features which, in turn, comprise the reference surfaces. A number of design options were considered:

*Steps.* The step gauge is an important artefact in verifying CMMs with moderate working volumes. Thus, an obvious choice for the reference surfaces
396 Laser Metrology and Machine Performance

on the LRA are steps with two or more flat surfaces, for example gauge blocks. The corresponding calibration information is a set of distances between selected plane, nominally parallel faces. The main advantages of this choice are:

- It represents a simple extension of step gauge principles familiar to users.
- It allows for simple, bi-directional probing strategies.

The main disadvantages are:

- The steps have to mounted accurately to achieve parallelism between faces.
- The calibrated distances represent only 1-dimensional information.
- The steps cannot be used easily to define calibration information if the artefact is configured as a 2-dimensional artefact using the base station.
- Any bending of the artefact will effect the parallelism of the faces (as well as the distance between the faces).

Spheres. Reference spheres (tooling balls) with high sphericity are readily available and have long been used in CMM verification as the reference surfaces for ball plates. The main advantages of this choice are:

- No special mounting alignment is required. The only requirement is that the location of the spheres is known accurately enough for CMM CNC programming.
- The calibration information can be in terms of distances between sphere centres or as (3-dimensional) positions in some fixed frame of reference. This applies equally to 1-, 2- or 3-dimensional configurations of the artefact.
- Spheres can be probed in a range of orientations.

The main disadvantages are:

- The calibration information depends on calculations of the sphere centre co-ordinates; however reliable algorithms and software are available for this task (see, e.g., Forbes [2]).
- The measurements are not truly bi-directional. This is of less importance for large volume CMMs where probing errors are likely to be small compared to the geometrical errors.

For the artefact described here, each measuring station carries a grade 25 (±1 μm sphericity) sphere of 20 mm diameter and made of silicon nitride. In addition to the 8 reference features on each 1 m-module, there are 4 auxiliary spheres or, in the case of the 0.5 m-module, 2 auxiliary spheres. These auxiliary spheres are of the same design as the main spheres but lie one in each of the planes that pass through the centre of every other of the main spheres and that are radial to the tube. With respect to the line of the measuring stations, these auxiliary spheres are mounted alternately at +90° and -90°; see Figure 1. These
auxiliary balls are an essential feature of the modules because they enable a calibration of the artefact to be performed on a standard-sized CMM and allow the measurements of the individual modules to be combined. They can also be regarded as reference features used to define additional calibration information.

The use of carbon composites, titanium and ceramic materials throughout has ensured that the artefact is of modest weight: the complete assembled artefact including reference features weighs less than 25 kg.

Another major factor in the design of the artefact system is its mounting. The main features of the design are:

- The artefact is mounted on a substructure carried by one central, light, stable pillar. The pillar can either be attached rigidly to the CMM table or weighed down using convenient masses.
- The substructure is also made from a carbon fibre tube, designed to be used as a package in which to transport the artefact.
- An additional support at one end provides extra stability for safety.
- The artefact is mounted kinematically on the substructure through spheres mounted on clamps that can be attached rigidly to the artefact. The artefact can also be suspended vertically using the same equipment.
- The position of the clamps on the artefact is to be chosen to minimise the artefact bending using the equivalent of Airy points. Alternatively the artefact can be simply supported.
- The design is capable of orienting the artefact in all the positions suitable for CMM verification according to ISO 10360-2 procedures.

3 ARTEFACT CALIBRATION

ISO 10360 requires that the length artefact used in a verification should be calibrated/stable to 20% of the accuracy of the CMM. An accurate large CMM may have a quoted length measuring capability of $\pm(10 + 6L/1000) \mu\text{m}$; with $L = 5000 \text{ mm}$, this amounts to $\pm40 \mu\text{m}$. Thus, the requirement for the artefact is that it is calibrated to $\pm8 \mu\text{m}$ and it must be stable to significantly better than this.

We propose to calibrate this (5 m long) artefact using a CMM whose longest working axis is 550 mm! We can achieve this using a repositioning method (Cox et al. [3,4]). This approach can be used for any measurement task which requires the artefact to be moved in order to probe all the relevant surfaces. The problem of relating measurements taken in different artefact positions is solved by attaching spheres rigidly to the artefact, either directly or through jigs, and determining the positions of (subsets of) the spheres 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 can then be transformed back into one frame of reference, thereby creating a self-consistent set of data points.

At NPL, we have developed software implementations of algorithms — position-calibration software — to provide unbiased estimates of the parameters linking the frames of reference and those specifying the centres of the spheres. The software also provides estimates of the statistical uncertainties of these parameters and related quantities such as the distances between specified pairs of spheres (Forbes [5], Butler, Forbes and Kenward [6]). The software is completely flexible with respect to the number of spheres, number of positions, measurement strategy, etc., and can provide automatically initial estimates of all the parameters. In addition, the software detects which, if any, of the spheres have moved relative to the others from position to position through monitoring the distances between spheres for the various positions of the artefact: if any sphere has changed its relative position then the set of distances between it and the remaining sphere centres will also change in general. A software module records the details of any change in distance greater than a pre-assigned tolerance.

This repositioning methodology can be applied directly to the calibration of the reference artefact using the reference spheres attached to the artefact. 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. The spheres in each coupling region are then measured and the sphere centres recorded. The individual measurement of each section of the artefact and of each coupling region between adjacent sections results in sets of measurements each taken in a different frame of reference. From these measurements, the position-calibration software determines the spatial relationships of the different frames of reference and transforms the data points to a common frame of reference. In addition, the software produces the calibration information in the form of the positions of the spheres in a fixed frame of reference (and consequently all inter-sphere distances) along with their uncertainties.

The repositioning strategy can be used to provide a complete calibration picture of the artefact through the measurements of the modules and their interfaces. However, it will not in general be possible to collect these measurements without disassembling and reassembling at least one of the joins. This means that the calibration of the artefact will only be valid if the geometries of all the coupling regions are the same when the complete artefact is assembled as when the measurements of these measurements were taken. It is for this reason that the joins are designed to provide highly repeatable kinematic links.

A second aspect to address is artefact distortion. Although the individual modules and joins are designed to produce a rigid artefact, there will be some bending of the artefact during its use. Initial calculations suggest that this will
not introduce significant errors if the artefact is regarded as a length artefact. However, if the artefact is regarded as providing 3-dimensional, this distortion effect could be significant.

There are two main approaches to compensating for any such distortion. The first is to determine corrections from a finite element model the artefact and its method of support. This is reasonably straightforward since the materials involved are adequately characterised and the geometry is simple. The second approach is to use reversal techniques to determine the degree of bend as the artefact is used. For example, suppose that the spheres mounted along the main measurement axis and those mounted laterally are measured for the artefact in one position. The artefact can be rotated through 180° about its axis and the positions of the spheres mounted laterally re-measured. From these measurements the degree of bending can be estimated (to the repeatability of the CMM) and compensated for. (Exactly the same strategy can be used to eliminate (or considerably reduce) the requirement that the joins are repeatable. In fact, a modest extension of these reversal techniques can eliminate the need to perform any extensive pre-calibration of the artefact).

4 ARTEFACT USE

The main use of the artefact is in the verification of large CMMs according to the principles of ISO 10360-2, regarding the artefact as providing calibrated lengths. The only difficulty in reconciling this use of the artefact with the standard specification is measurements of the spheres do not constitute bi-directional measurements. As mentioned above, it is generally the case that probing errors are not likely to be the main source of error in a large CMM. If necessary, some of the spheres can be replaced by gauge blocks in order to conform fully to the requirements of the standard. However, the artefact is more than a length artefact in that the sphere centres define 3-dimensional information, if only along a single axis: it is in effect a 1-dimensional ball plate or ball gauge (see, e.g., Zhang and Zang [7]). Numerical simulations at NPL have shown that such an artefact can be used to determine accurate estimates of CMM parametric errors if a suitable measurement strategy is used (Forbes and Harris [8]). Thus, it is quite possible that the artefact could be used to provide more comprehensive information on large CMM behaviour.

5 CONCLUDING REMARKS

In this paper, we have described the design, construction and calibration of a large reference artefact for use in CMM verification. The main points considered are:

- the use of tubular sections made from carbon composites.
- the use of ceramic reference spheres to carry calibration information, and
Laser Metrology and Machine Performance

- the use of repositioning methods to calibrate the artefact, employing the references spheres to determine frames of reference.

We believe that the artefact constructed is a practical approach to providing a reference artefact to extending the ISO 10360-2 verification procedures to large volume CMMs. The basic artefact design can be scaled up or down. Moreover, this type of artefact is expected to be of considerable value in determining parametric errors of CMMs or in performing CMM interim checks.

6 REFERENCES


