Dimensional metrology into the Millennium(1)

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Abstract

This paper covers some of the aspects of dimensional metrology likely to be important in the new millennium. Dimensional metrology will need to keep pace with manufacturing industry's rapidly advancing requirements forever more thorough inspection of parts. Although CMMs will attain higher speeds and data collection rates, holistic techniques will surely become increasingly important. Taking account of the influences of the thermal environment, both for the measuring system and the part to be measured, will remain a constant challenge to accurate measurement. Finally the "soft" aspects of dimensional metrology, such as operator training, understanding part specifications and uncertainties, software and measurement strategies will need special attention for the future.

1 Introduction

Dimensional metrology is the measurement science underpinning the needs of most manufacturers of components and products to demonstrate that parts meet their drawing specifications. In general, the technologies involved are largely mature, that is to say they have been known for many years, and based on a multitude of pre-existing techniques, except perhaps in the case of coordinate technology which had a most profound impact on dimensional measurement in the early 1960s.

Can we learn anything from the past to predict how dimensional measurement will evolve in the future? Certain trends are clear.

- there is, and has been for many years, a definite progression to more demanding dimensional tolerances driven by the functional requirements of parts.

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- the range of sizes of components is expanding rapidly. Whilst many precision parts can still be fitted into a shoe box, many parts are either too large for the conventional tool room, like the wing of an aircraft, or too small to handle conveniently, for example many of the elements associated with MEMS (micro electromechanical systems).

- the demands of production coupled with the need to inspect a greater proportion of the production output dictates faster measuring cycles – identifying bad parts is a key economic issue.

- the technologies associated with robotics, machine tools and CMMs will become increasingly interchangeable, customer requirements will force manufacturers to search for more cost effective technical solutions rather than automatically developing existing technologies.

- the thermal environment will always be a key factor in dimensional measurements. Thermal expansion of materials is seldom taken fully into account and the methods of measuring temperatures on real components is rarely giving the importance it deserves.

- the level of complexity of components is increasing at an enormous pace as well. This trend carries with it great benefits, reducing the need to join parts together and often improves part performance because there are fewer parts to go wrong. But there are potential shortcomings as well – it is frequently difficult to measure parts with complicated geometrical inter-relationships between features. The time taken to make such measurements is usually underestimated and is therefore an unexpected cost to the manufacturer.

2 Accuracy

The predictions of Tanaguchi and Moore are well known and often quoted, and point to a need for progressively tightening accuracy requirements. It is however questionable that their general predictions will remain on track too far into the new millennium – purely because of the physical and the cost constraints as requirements move towards and beyond the atomic levels of accuracy. The specialised requirements for the semi-conductor industry will always be challenging as circuits are needed to operate at an ever faster speed. Increasingly what were once research instruments for metrology, for example scanning electron microscopes, are being used routinely in high technology industrial processes ensuring the traceability of such measurements is not a straightforward undertaking.

Nevertheless, there are many examples where products in our everyday lives rely on nanometre scale accuracy, such as components at the heart of video-recorders and data storage media for computers. It is more than likely that similar, consumer-oriented products will emerge in the future with even more demanding accuracy levels.

In some areas there will be a move towards simpler hardware coupled with sophisticated software. Software is expensive to develop but can be replicated exactly at virtually no cost. Simple hardware requires less development cost and has a finite but tolerable unit cost. The use of powerful self-calibrating techniques will ensure that the instrument continues to function accurately even in the presence of temporal drift and environmental influences. A major aim for such hardware is to achieve excellent repeatability characteristics, even at the expense of relatively large systematic errors, coupled with adaptive error correction based on the model. Even for simple designs attention will be paid to this aspect. Coupled with these considerations will be the provision of measurement strategies which are designed to provide appropriate data for high-precision self-calibration.

Arguably the more straightforward dimensional measurements such as diameter, roundness, and so on, are keeping pace with industrial needs. Nevertheless there will always be examples where the buffer between the state-of-the-art and industrial requirements is uncomfortably narrow. For example, the time is fast approaching when the conventional coordinate measuring machine (CMM) will no longer meet the accuracy requirements of the national metrology institutes; indeed in some cases there will be barely any difference between the best industrial capability and the national capability. Up to now improved CMM designs have been based on refining the mechanical and software elements of a conventional CMM, i.e. where each axis is combined to the overall structure in a serial way by building one axis on another. At present it is most economical to reduce accuracy limitations created by the lack of perfection of the geometry-defining elements by compensating the measured co-ordinates by means of a software correction. However, such compensation techniques cannot, in any simple way, address the influence of the weight of the components being tested on the geometry of the system. Thus developing methods of creating CMM structures that are independent of the component being measured are the only foreseeable route to improved levels of accuracy

3 Size

Small

The trend towards miniaturisation in many fields, but especially MEMS has led to increased interest in research work to develop meso-scale CMMs(2). NPL has developed a CMM for accurate measurements on objects in the size range up to 50 mm in any, or all, three axes with a target accuracy of 50 nm. The justification for building such a CMM was strongly driven by the industrial requirements for accurate measurements of small components and features but with a view towards calibrating tiny reference artefacts with which to

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demonstrate traceability. Initially tiny (0.5 mm or 1 mm diameter) spheres will be used to touch the surface under test, but ultimately other systems will be used to probe components. Soft materials provide the most significant challenge because, in some cases, of the damage caused by even the lightest touch.

... and large

Increasingly components for aircraft, such as wings and fuselage sections, are being machined out of the solid material. Moreover, these components are being made so that no shimming or additional material is needed to ensure that they fit together perfectly. There are also many science-driven requirements in the field of astronomy that are already calling for measurements with hitherto unachievable accuracies. New generations of large-scale metrology instruments are already emerging to meet these needs. Crucially such instruments use the power of redundant measurement data to enable self-calibration techniques to be applied. In the future it is likely that the conventional large CMM as it is known now will disappear as it will become too cumbersome.

4 Fast measurement

With the trend for some safety-critical parts to be inspected completely, the time the measurement data takes to collect can be considerable. In the future, it is likely that techniques that collect dimensional data at essentially the same moment, the so-called "holistic" techniques, will find favour. After all, if a faulty part can be identified in a few seconds this might save vastly longer periods fruitlessly collecting measurement data from regions of the part that are perfectly satisfactory; such methods use holography, moiré fringes or photogrammetry techniques. Although many of these techniques have been, or are being, used already, it is their wider use that is likely to develop.

5 Cross-disciplinary technologies

Historically manufacturers of machine tools, of robots and of CMMs have developed their designs through an evolutionary process using measurement techniques, software and hardware that has been associated with the type of instrument or machine. In some cases this process has been highly successful with, for example, geometrical-error compensation being very successfully applied to CMMs in order to reduce the production costs of a CMM with comparable accuracy to an uncompensated CMM. Arguably the such techniques at the current state-of-the-art has not fed through to machine tools. On the other hand, work on the thermal influences associated with machine tools has not fed across into CMM technology. So in the future it is likely that there will be more sharing and exchange of technologies. This may very well also take place with the new generations of parallel linkage machine tools where some CMM and robot technologies overlap.

6 Design complexity

CMMs have played a key role in dimensional metrology for many years. Countless components can only be measured on CMMs because of their complex shape and correspondingly complicated drawing indications. In many cases no drawing at all exists for a part – just a computer data file and so the CMM approach is the only way to go. This is borne out by the thousands of CMMs being used worldwide. There are countless examples where co-ordinate measurement is used to critically inspect production parts, whether it is the size and position of bores in a gearbox that ensures the gears fit and run true, to measuring the size of an aircraft wing to reduce the use of heavy shims when it is fitted to the fuselage.

In the longer term, emphasis will move from the assessment of measured data on a feature-by-feature basis, with links provided by datums and other information. A much more holistic approach will be entertained, with measurements on complete workpieces being provided to assessment software, which will examine and process it as a whole in order to test product conformance. Even if the measurements on different features are made in different reference frames, all such measurements will be fused appropriately, perhaps *via* the use of additional measurements taken for this purpose on a number of reference or registration features.

Worryingly, the dimensional results provided by a CMM have become regarded by their users as being correct, irrespective of whether proper steps have been taken to demonstrate the traceability of the co-ordinates that it measures. Maybe users think that an instrument that is so very expensive cannot be wrong! However, the introduction of Quality Management Systems has meant that such assumptions cannot be made and CMM users will have to show that their measurements are valid, otherwise they will be in costly disputes with suppliers, customers and sub-contractors.

7 Traceability

In common with all other measurements, dimensional measurements must be traceable to the SI unit. In many cases this is simple, for example for a micrometer or vernier calliper where one parameter is measured. However, the versatility of the coordinate measuring systems such as CMMs, photogrammetric cameras, laser trackers, and so on, makes demonstrating traceability difficult. There are essentially two ways to achieve traceability:

- evaluate *all* possible sources of uncertainty

- use the CMM as a comparator between the test object and a calibrated object or similar characteristics

Uncertainty evaluation of the results of a series of measurements on one feature of a component is possible but when many features and many parts are involved this process becomes very complex. The reason is that every measurement point that is taken will influence the uncertainty of the overall result. Solutions to this are evolving, but such solutions are not simple and rely on a detailed knowledge of the sources of uncertainty of the co-ordinate measuring *system*, i.e. all aspects of the CMM itself, its environment and the operator. However, once relevant information has been collected then mathematical modelling and simulation techniques can be applied which do predict uncertainties for any measurement. It is an exciting approach and in a few years time it will provide the neatest and almost universal solution. It will be best suited to the CMM user who must measure many components of various sizes and shapes with large numbers of features.

Reliable uncertainty evaluation will remain a challenging task. However, the use of sound models and supporting software tools will help to deliver realistic uncertainties for many problems. An inverse approach will be increasingly employed in which a target uncertainty is initially set and a measurement system is designed or adapted to meet this target. Numerical optimisation techniques will be used extensively to determine system-parameter values to meet the target or to demonstrate that a prescribed target is physically infeasible. Moreover, these techniques will also be used to define measurement strategies that deliver a target uncertainty with economy of measurement.

The use of mechanical reference artefacts is an alternative approach for the CMM user who needs an economical solution now and does not have large number of critical components for which traceability has to be demonstrated. The technique is very simple – the CMM user identifies the sorts of components most commonly measured and chooses an artefact that embodies the key geometrical elements and sizes. This artefact, or range of artefacts, is measured to a high level of accuracy and then measured with the user's CMM. Provided that the artefact closely resembles the measured parts the uncertainty of the measurements can be evaluated and hence traceability demonstrated. International standards are well advanced to back this technique known are the *substitution, or comparator* technique. However, the calibrated artefact route to traceability does rely on a source of calibrated components. If affordable traceability for the dimensions of a wide range of components is to be achieved for industry, high accuracy certified artefacts will be required to support this need.

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8 Software and liveware

Having reviewed many of the more instrumental issues of metrology in the new millennium, it is more than likely that software and liveware (the operator) will provide both the key and the barrier to new developments.

Software: already plays an important role in dimensional measurement – it is very evident in CMMs but now in many other instruments. Sometimes it is used to compensate for a lack of geometrical perfection, sometimes to process results, sometimes to compute the inter-relationship between features on a part. The hidden danger is that the use does not know what it does and whether it is operating correctly. Thus demonstrating the integrity of the metrology software is, and will remain, a major challenge for the next millennium.

Although the software component of many measurement systems is today appreciable, enormous advances in instrumental software can be anticipated. The hardware-software compositional balance of CMMs and other sophisticated instruments will shift ever further towards software aspects. Tomorrow's software will provide an enhanced ability to inject greater "intelligence" into the measurement process and to yield increased accuracy, efficiency and versatility. This is not to say that software advances will generally *replace* their hardware counterparts, although this will be the case in some instances. Rather, the software will provide the "glue" that integrates new and existing hardware to deliver an overall, adaptable instrument, as well as providing major support, particularly for the special-purpose machines used at the highest levels of measurement traceability by the national measurement institutes.

Good CMM and other measurement software is necessarily supported by *mathematical modelling*, a discipline that will grow ever more strongly in its impact on dimensional metrology. This emphasis on mathematical modelling is part of a trend that will persist as greater physical understanding of measurement processes and systems is gained and an increasing number of analytical tools are applied. Such modelling also facilities the provision of traceable measurement uncertainty in accordance with the approach recommended in ISO GUM, the international guide to the expression of uncertainty in measurement.

The construction of mathematical models that are increasingly more realistic will provide a basis for a wide range of fruitful investigations and advances in dimensional metrology and permit, among many possibilities:

- Simulation of instrument behaviour
- Optimisation of instrument design
- Design of optimal measurement (probing) strategies
- Better understanding of form error
- Conformance checking (of workpiece against specification)
- Improved systems operating under the self-calibrating principle
- Uncertainty evaluation of increased validity

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- A basis for high-quality algorithmic and software solutions.

In dimensional metrology the emphasis will move ever more towards strongly-integrated hardware-software systems. Mathematical modelling based on physical understanding and careful analysis will provide the basis for appropriate algorithmic solutions and high-quality software implementations. Software will control and link ever more closely the various component parts and sub-systems.

Simulated instruments will take a leading place in tomorrow's dimensional metrology, providing a role in training and education, as well as a major preparatory role in advance of actual measurement. Optimal task-specific measurement strategies will be prepared which will provide results of the highest precision at the highest levels of traceability as well as reliable solutions obtained economically for industrial need.

Associated-feature-fitting algorithms will be significantly improved from the current position, not only in terms of providing Gaussian (least-squares) algorithms which are more reliable and capable of covering measurements on wider range of features, but also in terms of the alternative measures, Chebyshev and one-sided, which have broader industrial applicability.

Liveware: the operator is another somewhat intangible factor in the measurement process. It is clear from much research work already performed that optimising the spatial distribution of measurement points on a surface will have a dramatic influence on the uncertainty. Unless the operator is knowledgeable, not using the optimal distribution will become a significant source of uncertainty. This is not the end – there are a host of other factors where a knowledgeable operator can deliver the best measurement uncertainties, but conversely an inexperienced operator can introduce uncertainties that are far larger than the contributions from the measuring instrument or even the environment.

9 Conclusions

Dimensional metrology offers some exceptionally demanding challenges and some fascinating opportunities for this millennium. However, whatever the measurement task, no doubt a subtle mixture of the right equipment, reliable software and an experienced metrologist will be needed to provide the optimum solution.

End Notes

(1) This paper was first presented at the International Dimensional Metrology Workshop 2000 in Knoxville in May 2000.

(2) From the Greek word for intermediate; i.e. the working volume and accuracy of the system is intermediate between the conventional CMM and the scanning probe microscopes.

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