Performance verification for large volume metrology systems

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Abstract

A method for the verification of the performance of conventional co-ordinate measuring machines is defined in the ISO 10360-2 standard. This specifies how measurements of a set of traceable lengths (for example, step gauges, length bars, etc.) can be used to verify whether the length measuring capabilities of a given instrument are within the manufacturer's specification. Large volume measurement systems such as the laser tracker, photogrammetry, portable arm CMM's and theodolite systems are not specifically addressed by the ISO 10360-2 standard. However, these systems are increasingly being used in high value processes and the requirement for verification procedures for such systems is clear. Extending the principles of ISO 10360-2, this paper describes a consistent and comprehensive method for the verification of large volume measurement systems.

1 Introduction

This paper is concerned with verification procedures for large volume metrology systems [1]. Any such procedure will involve value judgements based on various competing requirements. For instance, however desirable it might be to have thousands of measurements it may only be possible to take a few hundred. Some key issues are the following:

- **Practicality** - any procedure has to be carried out within a time period acceptable to the end-user and the physical requirements and cost must not be prohibitive.

- **Confidence** - the procedure should have sufficient redundancy to ensure statistical reliability such that no significant shortcomings of the measurement systems go undetected.
- **Transparency** - the user should be able to easily understand the procedure, interpret the results and be able to make valid inferences about measurements made in similar working volumes and conditions.

The main components of the verification methodology described below are as follows: 1) a mathematical model of the nominal system behaviour described in terms of statistical properties of the measurement sensors and the system configuration, 2) estimation of the uncertainty in the distance between any pair of points in the working volume derived from the mathematical model, 3) repeated measurement of a length artefact, 4) comparison of the measurement data with the uncertainty model, and 5) derivation of a statement of system performance. In this paper, this methodology will be illustrated for laser tracker and photogrammetric systems. The methodology can also be applied to theodolite and portable arm CMM systems, for example.

2 Theory

The verification of the length measuring capabilities of a co-ordinate measuring machine (CMM) according to the principles of ISO 10360-2 [4] is based on the following components:

- a statement of the length measuring capability of the CMM,
- calibrated length artefacts,
- measurement of the length artefacts,
- comparison of the estimates of the lengths derived from the CMM measurements with the corresponding calibrated values.

The scheme is quite generic and can be adapted to verify the length measuring capability of any co-ordinate measuring system (CMS). The effectiveness of the scheme depends largely on (a) the appropriateness of the statement of capability, (b) the adequacy of the measurement strategy and (c) the availability of suitable length artefacts.

2.1 Statement of capability

For conventional CMMs, the statement of length measuring capability takes the following form:

Given an artefact of calibrated length L, the estimate of its length $\hat{L}$ derived for measurements should depart from its calibrated value by no more than $A + B / L$, i.e.,

$$\left| L - \hat{L} \right| \leq A + B / L.$$

Thus, the capability is specified by the two constants A and B. That the above equation does not involve the location of the artefact within the working volume reflects the isotropic behaviour of CMMs: the errors in one area of the CMM are comparable with those in any other area.

A more general statement of length measuring capability is:

> Given a length artefact of calibrated length L, the estimate of its length $\hat{L}$ derived for measurements $\mathbf{x}_L$ and $\mathbf{w}_L$ satisfies
>
> $$\left|L-\hat{L}\right| \leq A(\mathbf{x}_L, \mathbf{w}_L),$$
>
> where $A(\mathbf{x}_L, \mathbf{w}_L)$ is a predefined function.

The dependency of the *capability function* A on location allows for any anisotropic behaviour to be taken into account.

We now describe a general approach for defining suitable capability functions for large volume measuring systems. The estimate of a target coordinates $\mathbf{x}_j = \mathbf{x}(\mathbf{u}_j, \mathbf{b})$ by a CMS depends on two sets of information a) the *sensor readings* $\mathbf{u}_j$ and b) the *configuration parameters* $\mathbf{b}$. For a conventional CMM, the sensor readings are the scale measurements; for a laser tracker they are the two angle measurements and the interferometric displacement measurement; for a photogrammetric system, the co-ordinates of the target on a two-dimensional image. The individual sensor readings are associated with a single target location. The configuration parameters are those that influence a number, or all, of the targets estimates. For a conventional CMM, they can include the probe offset and diameter and parameters specifying the error correction map; for a laser tracker they include the parameters specifying the tracker location and orientation and the offset associated with the interferometric displacement, for example; for a photogrammetric system, they specify the camera locations, orientations and optical characteristics.

The target estimation function $\mathbf{x}_j = \mathbf{x}(\mathbf{u}_j, \mathbf{b})$ may be straightforward and explicitly defined, as in the case of a conventional CMM or a single laser tracker, or defined implicitly as the solution of a nonlinear system of equations as in the case of theodolites, photogrammetry and multiple laser trackers. In all cases, however, the nominal behaviour of the system can be defined completely in terms of the geometry of the system (i.e., the position of the measuring stations and targets) and the target estimation function can be derived from geometric principles.

The uncertainty in the target estimates will depend directly on the uncertainty in the sensor measurements and the estimates of the configuration parameters. A statement of the uncertainty of the sensor measurements can be converted into a statement of the uncertainty in the target location using the laws of propagation of uncertainties [3]. For example, if $\mathbf{u}_j = (u_{j,1},...,u_{j,p})^T$ and $u_{j,q}$ has variance σ_q^2, then the variance $\sigma_{j,k}^2$ of the *k*th component $x_{j,k}$ of $\mathbf{x}_j$ is given by

$$\sigma_{j,k}^2 = \sum_q \left(\frac{\partial x_{j,k}}{\partial u_{j,q}} \right)^2 \sigma_q^2.$$

(These variances can be visualised as error ellipsoids centred at the target location.) In this way, from a statistical model for the sensor measurement and configuration parameters we can derive an estimate of the standard uncertainty $u_{\mathbf{b}}(\mathbf{x},\mathbf{w})$ of the distance between any two points $\mathbf{x}$ and $\mathbf{w}$ in the working volume of the CMS. The subscript $\mathbf{b}$ indicates the function depends on the configuration of the system. The capability function can then be expressed as a suitable multiple of u:

$$A(\mathbf{x}_L, \mathbf{w}_L) = K u_{\mathbf{b}}(\mathbf{x}_L, \mathbf{w}_L) .$$

2.2 Comparison of measurements with capability statement

The derivation of the capability function described above is based on a statistical model of CMS behaviour. It is therefore appropriate that the comparison of measured lengths with their calibrated values is also statistically based. The function $u_{\mathbf{b}}(\mathbf{x},\mathbf{w})$ gives the standard uncertainty in the measurement of length from $\mathbf{x}$ to $\mathbf{w}$, i.e., the expected deviation in the length measurements at these locations from the true value. Assuming the errors are normally distributed, we would expect approximately 95% of these measurements to be within $2u_{\mathbf{b}}(\mathbf{x},\mathbf{w})$ of the calibrated value. If we expect the errors at different locations to be largely uncorrelated (and normally distributed) then given measurements $\hat{L}_j$ of lengths L_j at pairs of locations $(\mathbf{x}_j, \mathbf{w}_j)$, we expect

$$\left| L_j - \hat{L}_j \right| \leq 2u_b(\mathbf{x}_j, \mathbf{w}_j),$$

to hold for 95% of the measurements. In general, the degree of conformance is measured by the actual deviation of the measured lengths from their calibrated values compared with the expected deviation described by the capability function. The comparison can be defined to take into account correlation in the measurements and uncertainty in the calibrated values of the length artefacts.

3 Verification of a laser tracker

3.1 Creation of a traceable length artefact

We illustrate the general approach first by describing experiments with laser trackers using the NPL large reference length artefact [2]. A practical problem encountered with laser trackers is that the performance of the interferometer has an accuracy specification of 2.5 parts per million (in a stable environment). If the artefact is to be five to ten times more accurate than the interferometer then this implies the length artefact should be better than 0.5 microns per metre. This requirement is beyond current artefact technology. (The NPL artefact has an uncertainty of approximately 1.5 microns per metre.) A more pragmatic approach is to verify the interferometer at manufacture against another traceable interferometer standard. For a verified interferometer, a bootstrap strategy can be adopted in which a length artefact is located as close as possible to the tracker and measured using an accurate spherical retro-reflector along a radial measuring line, The artefact is then reversed and the measurement strategy repeated. In this situation, the tracker is used in its optimal mode and these measurements, along with any prior calibration information, create a temporary calibrated reference artefact. The artefact can then be used to assess the behaviour of the system in which errors associated with the far and medium distance capability of the interferometry (including refractive index effects), the absolute distance-measuring device (if fitted), the angle encoders, and the laser displacement deadpath ("birdbath distance") are significant. This approach was used in the verification trials and proved to be valid.

3.2 Verification of the performance of the interferometer against its specification

The first set of experiments were designed to assess the performance of the interferometric displacement measurements. The error ellipsoids for the configuration is illustrated in Figure 1.

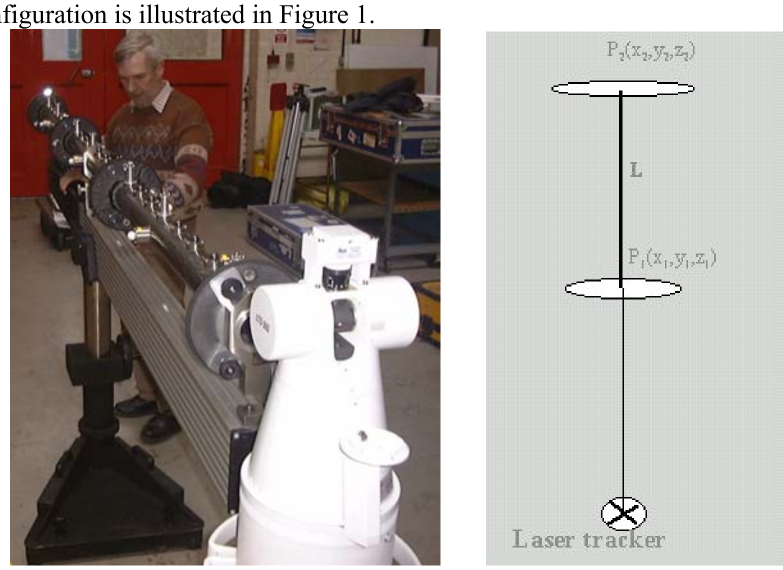


Figure 1. Practical set up for procedure and error distribution for the laser tracker and artefact during interferometer assessment

The temporary reference length artefact was placed at three locations, i.e., far (average distance = 17.5 metres), middle (average distance = 9 metres) and near (average distance = 1.9 metres), with respect to the laser tracker. Nine points on the artefact were carefully measured by the laser tracker (each of them six times, three on face one and three on face two). The 36 measured lengths between those points were then compared with the calibrated lengths of the artefact. At each artefact location, 216 lengths were compared. The absolute differences between the measured lengths and the calibrated lengths were considered laser tracker's length measurement errors. The actual measurement errors and the predicted uncertainties for 9 metre location are plotted in Figure 2. The predicted uncertainties, derived from the manufacturer's specification of sensor behaviour, were in general greater than 30 micrometres and the measured errors less than 20 micrometres, indicating that the performance of the interferometric displacement measurement was within specification.

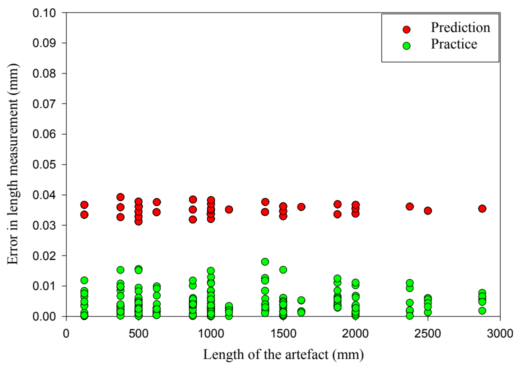


Figure 2. Comparison between the predicted accuracy and that obtained in practice for the interferometer at a distance of 9 metres.

3.3 Verification of the performance of the horizontal angle encoders against specification

To verify the horizontal angle measurement performance the artefact was placed horizontally at right angles to line joining the tracker location to the midpoint of the artefact as shown in Figure 3.

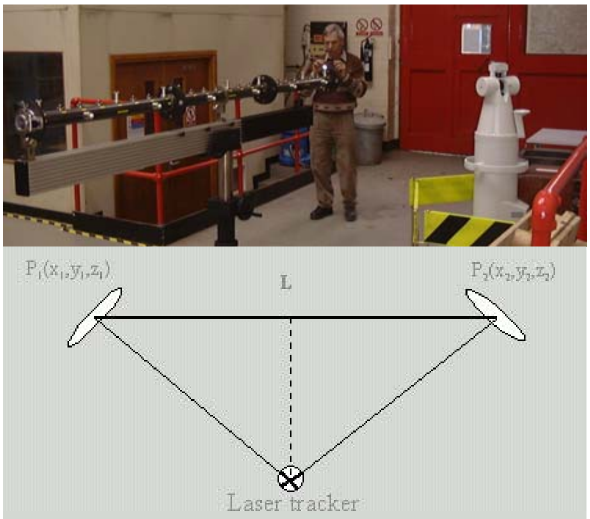


Figure 3. Practical set up of the verification procedure for horizontal encoder assessment and expected error distribution for angle measurements

Each of the nine points on the artefact were measured six times (three for each face) with the artefact placed about 2 metres away from the tracker. The body of the tracker was rotated through three 90 degrees to complete the three further quadrants. A total of 864 lengths were measured. The absolute differences between the measured lengths and the calibrated lengths (the length measurement errors of the laser tracker) were compared with the predicted uncertainties. The artefact was then placed to a further distance (9 metres) away from the laser tracker. Only one quadrant was tested. The results of 216 length measurements were plotted in Figure 4. The results showed that the length measurement errors of the laser tracker were all less than the predicted uncertainties.

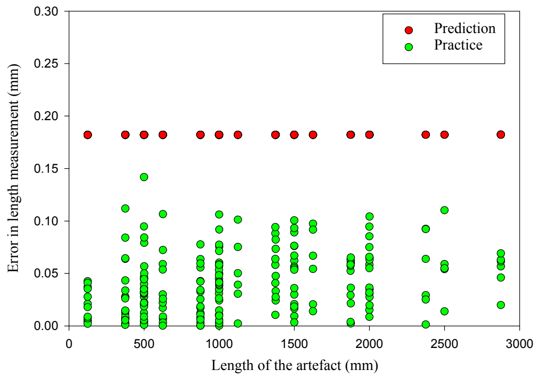


Figure 4. Comparison between the predicted accuracy and that obtained in practice for the angle encoders at 9 metres.

3.4 Results of the verification experiment

The methodology proved to be both sensitive to errors and also a practical procedure; the complete set of experiments could be carried out within a period of 4 hours or so. In this example, the capability of the measurement system was verified to be within its specification.

4. Verification of a photogrammetric system

4.1 The specification for a photogrammetric system

The same scheme as implemented in section 3 has been applied to a stereo photogrammetry system. A model for the system is used to predict the non-isotropic behaviour and length measurements are compared with the predictions. However, in the case of photogrammetry there is no commonly agreed means of specifying the performance. Manufacturers often provide a one or two sigma measurement precision as a proportion of the largest dimension of a measurement volume, e.g., 1 part in 100,000. The capability function $A(\mathbf{x},\mathbf{w})$ has a complex form, depending on the position of the cameras and the number of views of a given target. However the general principles described in section 2 can be applied to derive a capability function. A photogrammetric camera acts as an angle measurement device and the commonly accepted internal model assumes equal accuracy at all points in the image plane. An internal measure of image accuracy is provided by what are termed "image residuals", the differences between the original image observations and the projections from object to image space (using the photogrammetry system model) of the 3-D estimates of the object targets. The standard deviation of these residual errors has been chosen as the prime indicator of system performance on which the uncertainty model is based.

4.2 Verification strategy

The basic scheme implemented for verification of photogrammetry systems is to use reference lengths comparable with the dimensions of the measurement envelope of the system being tested. The reference lengths can either be physical, consisting of an artefact with at least five targets in known positions, or *virtual,* being the measured location of a single target moved to various positions. The auxiliary measurement system might be a CMM, a laser tracker or an interferometer. The real or virtual reference lengths are position in a number of locations and measuring lines within the working volume of the measurement system, for example, along its X, Y and Z axes and various diagonal and compound diagonals.

4.3 Data collection

The configuration of the stereo system with respect to the virtual length artefact is illustrated for one of the configurations in Figure 5.

Figure 5. Configuration for verification

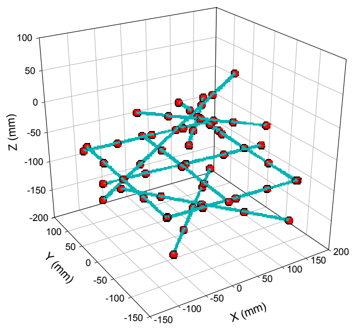
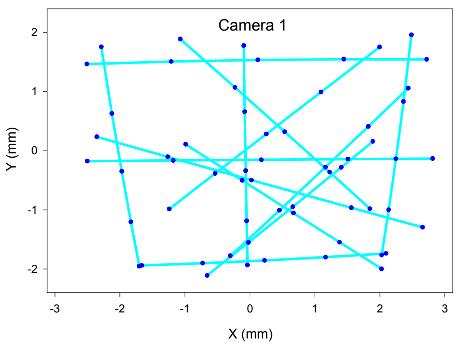


Figure 6. Arrangement of virtual length artefacts

In each configuration, measurements of a number of traceable lengths were collected. The 3-D arrangement for the various lengths is illustrated in Figure 6. The measurement envelope for the system under test is not a simple shape as it is defined by the mutual overlap of the two camera views. At each of the measurement locations, illustrated by the blob on the line, the interferometer reading was noted along with the 3-D measurement of the target using the photogrammetry system. To illustrate the fact that this strategy is a good test of the camera calibration Figure 7 illustrates the position of the target and the line of the virtual artefact measurements.



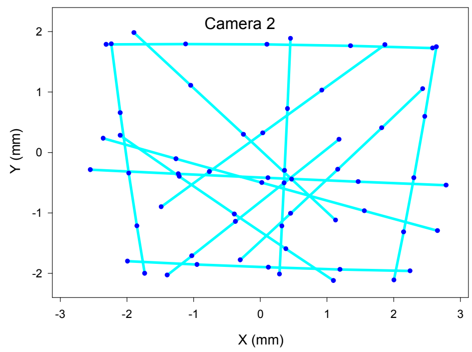


Figure 7. Position of the targets and virtual length artefact in both images.

The 3-D co-ordinates of the target at each location (computed by intersection with known camera exterior parameters) were used to calculate the distances between adjacent two locations. If the absolute differences between the measured distances and the traceable lengths are less than estimated uncertainty of the distances the system is verified. If the stereo system specification is verified, the method of specifying the performance of photogrammetry systems can be also be considered valid. The specification can then be used to predict the performance of the system in other configurations. The results of the verification are illustrated in the following figure.

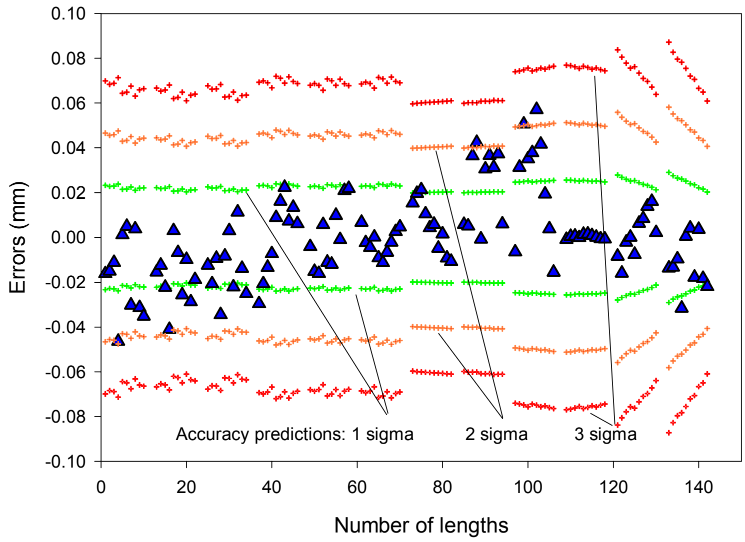


Figure 8. Verification results from all measurements

If enough samples are taken and a normal distribution of errors is expected then some 68% of errors will be within 1 sigma of the mean, 95.5% within 2 sigma and 99.7 % within 3 sigma. Given the distribution of errors in the example, this system passed the verification test.

4.4 Results of the verification experiment

The verification methodology has been applied to various stereo camera systems. The results showed that the method was sufficiently sensitive to indicate whether these systems were inside the specification or not. The work also confirmed that the approach adopted for specifying the performance of these systems was valid.

5 Conclusions

The verification methodology discussed in this paper extends the principles of the ISO 10360-2 standard for CMM's. The following advantages of the scheme can be outlined:

- The methods are based on appropriate models of system behaviour that properly take into account the anisotropic behaviour and its dependence on system configuration.
- The models of nominal behaviour for each system can be derived from relatively simple principles of geometry and statistics.

- The measurements involving the traceable lengths provide sensitive measures of the performance characteristics of each system.
- Analysis of the results is straightforward, rigorous and can be implemented in a simple software module.

The methods developed are direct and practical and could form the basis for an extension of the ISO 10360-2 scheme to large volume measuring systems, providing the required infrastructure to support quality control in many high value industries.

6 Acknowledgements

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7 References

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